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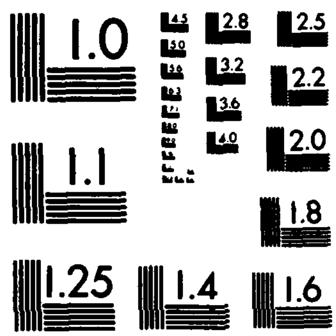


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# SOLAR KILNS

## FEASIBILITY OF UTILIZING SOLAR ENERGY FOR DRYING LUMBER IN DEVELOPING COUNTRIES

FPL-AID-PASA TA (AG) 02-75 (Solar Kilns)

January 1977

U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE
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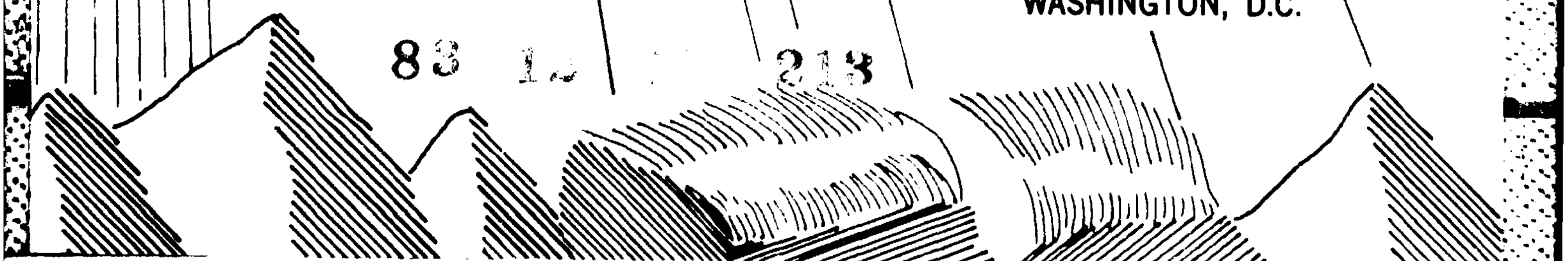

## ACKNOWLEDGMENT

The authors wish to thank certain personnel of the Forest Products Laboratory: Joan Lengel and James Haskell of the Statistics and Numerical Analysis Group, and technicians Tedd Mianowski and Alberto Villareal in the Improvements in Drying Technology Work Unit.


## PREFACE

In 1975 the U.S. Forest Products Laboratory (Forest Service, U.S. Department of Agriculture) entered into a research agreement with the U.S. Agency for International Development to conduct a research study on the feasibility of using solar energy to improve the drying of lumber processed by small- and medium-scale producers in developing countries. The scope of the study includes a literature review of solar lumber drying throughout the world, feasibility estimates, and the design elements of solar kilns that can meet the feasibility requirements. This final report on the project proposes two kiln designs that have good potential to provide low-cost kiln capacity.

The concept of the study has world-wide application. For the purpose of specific feasibility estimates and design details, a specific location, the Republic of the Philippines, was chosen. However, the kiln designs are applicable to any low-latitude location where low-cost kiln capacity is needed.

The assistance and cooperation of the Forest Products Research and Industries Development Commission (FORPRIDECOM) of the Philippines was extremely valuable in developing the background information necessary for the feasibility estimates and kiln designs. Commissioner Francisco Tamolang of FORPRIDECOM, Mr. R. E. Casin, and Mr. T. G. Cuaresma were particularly helpful in developing this information.

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# SOLAR KILNS: FEASIBILITY OF UTILIZING SOLAR ENERGY FOR DRYING LUMBER IN DEVELOPING COUNTRIES

By

John L. TSCHERNITZ, Chemical Engineer

and

William T. SIMPSON, Forest Products Technologist

Forest Products Laboratory, Forest Service
U.S. Department of Agriculture

## SUMMARY

A substantial portion of wood exported from developing countries is in the form of logs. To aid their economic growth, these countries are emphasizing increased domestic processing of logs into lumber or finished products. Improper, or lack of, lumber drying has deterred this "value added" manufacturing. Solar kilns can offer low-cost drying capacity. This study tested the feasibility of using solar energy to improve lumber drying by small- to medium-scale operators in developing countries. A literature review confirms the potential of solar drying and points out the success or failure of some design features, construction details, and applications of solar dryers. Feasibility estimates concluded that solar drying is practicable if a dryer meets production and cost requirements. Two dryer designs, a greenhouse type and an external-collector type, were proposed. Their production capacity was estimated by a material and energy balance analysis, and their construction costs were estimated.

# STATE OF THE ART

## LUMBER DRYING

Importance of Lumber Drying

The dry kiln represents the only practical means now in wide use for drying lumber to conditions optimum for maximum serviceability of

[1] The Laboratory is maintained at Madison, Wis., in cooperation with the University of Wisconsin.

many wood products. A well designed dry kiln, properly operated, can in a relatively short time transform green (wet) lumber into a dry, stable material for industrial use. The more critical the drying requirements, the more firmly the dry kiln becomes established as an integral part of the lumber and wood product processing scheme. For many wood products, kiln-dried lumber is indispensable.

Well dried lumber has many advantages for producers and users alike. Removal of excess moisture reduces weight and, thereby, shipping and handling costs. Proper drying confines subsequent shrinkage and swelling within small limits under all but extreme conditions of use. Properly dried wood can be cut to precise dimensions and machined more easily and efficiently; wood parts are more readily and securely fitted and fastened together with nails, screws, bolts, and adhesives; warping, splitting, checking, and other harmful effects of uncontrolled drying are largely eliminated; paint, varnish, and other finishes are more effectively applied and maintained; and decay hazards are eliminated if the wood is subsequently treated or protected from excessive moisture regain.

## Lumber Drying in Developing Countries

While a substantial portion of wood exported from developing countries is in the form of logs, emphasis and, in some cases, legislation is being generated in these countries to increase domestic processing of timber into lumber, veneer, dimension, and even finished products to take advantage of the obvious social and economic benefits created by each additional operation performed in the country. These industries are labor intensive, and "value added" manufacture is significant. There is substantial potential for expansion to meet growing domestic and export opportunities if quality products can be maintained. Improper drying of wood or lack of any controlled drying have been deterring factors in the increased acceptance of this "value added" processing in developing countries for both local or domestic use and export as a commodity in the form of lumber or secondary wood products.

For many end uses and secondary manufacturing processes, lumber should be dried to avoid undesirable effects during use. This is especially true in products such as furniture, cabinets, moldings, flooring, sash, doors, wood carvings, and other handicrafts that will be used in temperate countries.

Most small-scale woodworking operators in developing countries lack the facilities required to dry lumber. Air drying is useful but has some limitations related to drying defects, a slow rate of drying, and high final moisture content in humid climates. Air drying also involves maintaining fairly large inventories of lumber, which most small operators cannot afford. Conventional dry kilns powered by petroleum-based fuels are expensive to install and operate, and are beyond the means of the small operator. The problem, therefore, is the lack of a low-cost (both initial expenditure and operating cost) procedure which will dry lumber faster and to a lower moisture content

than will air drying, and that will do so with a minimum of drying defects. Solar drying may be the solution to that problem.

### Solar Drying of Lumber

Solar drying can offer an alternative to both air drying and kiln drying in a conventionally heated dry kiln. Solar drying in a properly designed solar kiln is faster than air drying. In a solar kiln a lower final moisture content can be attained than in air drying, which makes solar-dried lumber suitable for furniture and other high-quality uses. In general, the quality of solar-dried lumber should be better than that of air-dried lumber because it is protected from alternate wetting by rain and drying by direct rays of the sun.

## TECHNOLOGY OF SOLAR ENERGY COLLECTION

### Solar Radiation

Solar radiation reaches the earth in the form of electromagnetic waves. Most of this energy is contained between the wavelengths of approximately 0.28 to 4 microns. The intensity of this radiation beyond the earth's atmosphere is approximately 1.94 cal/($cm^2$)(min) or 429 BTU/($ft^2$) (hr). As the sun's radiation passes through the earth's atmosphere it is scattered and absorbed by dust, water vapor, ozone, and other gas molecules, so that the intensity of the radiation reaching the earth is less than 1.94 cal/($cm^2$)(min). The larger the air mass (the longer the length of the path through the atmosphere), which depends on the time of year, the smaller the fraction of radiation that reaches the earth's surface. Some of the radiation which is scattered by the atmosphere still reaches the earth's surface in the form of diffuse radiation.

The amount of direct (i.e., not diffuse) radiation that reaches a surface on the earth depends on a number of factors. It depends on the altitude of the sun (the angle above the horizon) which in turn depends on the latitude of the surface, the declination of the sun, and the hour of the day. Elevation above sea level (barometric pressure) also affects the air mass. The angle of incidence, the angle between the direct solar rays and a line normal to the irradiated surface, affects the intensity of the radiation. The orientation of the surface in relation to the sun (the wall azimuth and tilt of the surface) and the solar altitude determine the angle of incidence. The angle of incidence is also important because it determines how much of the direct solar radiation is reflected, transmitted, or absorbed. In addition to the direct radiation, a surface also absorbs diffuse radiation and any solar radiation reflected by surrounding surfaces.

If there were no cloud cover, direct radiation would be by far the

predominant source of radiation on a receiving surface, and the intensity would be quite easy to estimate fairly closely by the trigonometry involved. Cloud cover does exist and is quite variable and unpredictable, however. This increases the fraction of the total radiation that is diffuse and makes estimates of total solar radiation received on a surface difficult. Records of local solar radiation, preferably over a long period of time, are the best estimate when such records are available (U.S. Department of Commerce, Weather Bureau 1968; Löf et al. 1966). When actual radiation data are not recorded, but percentage of possible sunshine is, it is fairly easy to make reasonably accurate estimates of solar radiation. A horizontal surface receives a large range of actual solar radiation throughout the world and throughout the year. Some of the poorer sites (excluding extreme latitudes) may barely receive 300 Btu/(ft$^2$)(day) in the summer months. Averaged over the entire year some of the poor sites may receive less than 1,000 Btu/(ft$^2$)(day), and some of the better sites may receive over 2,000 Btu/(ft$^2$)(day).

## Collecting Solar Energy

Solar energy can be collected directly or indirectly. A greenhouse represents the direct type of collection. A concentrating device or a flat plate collector are two common types of indirect collection devices. Flat plate collectors appear to be more suitable for drying applications than do concentrating devices because lumber drying is a relatively low-temperature process, and, as such, flat plate collectors are adequate. In general, a flat plate collector consists of a cover, an energy absorbing surface, some means of heat transfer, and insulation if appropriate.

### Cover materials

From a technical standpoint low iron content glass has been the preferred glazing material because of its high transmission (greater than 90 pct.) of incoming solar radiation and its high degree of opacity to longwave radiation emitted by a collector plate. Plastic films have received attention as glazing material because of the relatively low cost of some types. The different types possess a wide range of such important properties as light transmission, strength, thermal expansion, resistance to ultraviolet radiation, as well as cost. In general, the plastic films have a relatively high transmission to longwave radiation, which reduces collector efficiency.

### Collector plates

Metals are normally used as the absorptive surface for collector plates in indirect collection systems. Copper, aluminum, and steel are the three most common collector plate metals. Copper has the best conductivity, but is also the most expensive. If the entire surface area of a collector plate has direct contact with the heat transfer

fluid (as in air collectors) conductivity is less important.

In early efforts to collect solar energy, flat black paint was used to coat the collector plate to increase absorption of solar radiation. In recent years selective surface coatings have been developed that are highly absorbent to incoming solar radiation, but have a low emittance for longwave radiation. They are generally experimental materials and are very costly.

### Heat transfer

Solar collectors normally use either water (with ethylene glycol in northern climates) or air as the heat transfer fluid. The principal advantage of water systems is the higher heat transfer rate between metal and water. Air collectors have the advantage of no freezing problems, and leakage problems are much less serious than leakage problems in water systems. For a drying process, where the drying medium is heated air, a liquid system would have the cost disadvantage of requiring a liquid-to-air heat exchange.

### Collection efficiency

The efficiency of solar collection is based on the total incoming radiation and the portion that can be converted to useful heat. The loss due to reflection at each glazing-air interface is approximately 4 percent for angles of incidence up to 35 degrees. Losses from energy absorbed by the glazing can also be significant. Losses up through the glazing can be very large and are divided into two types; transmission of long-wave radiation emitted by the collector plate, and the conductive-convective losses through the glazing to the outer air. This latter loss results in a decrease in collector efficiency as the collector temperature increases. Collector efficiencies are generally highest at solar noon, and drop off very rapidly beyond 3 hours from solar noon. A collector operating at solar noon at a low temperature might have an efficiency in excess of 60 percent. At 3 hours from solar noon a collector operating at high temperature might have an efficiency as low as 10 percent.

### Storage

There are two general types of storage associated with solar energy collection, specific heat storage and salt hydrate storage. Specific heat storage using either water or rocks is one means. The advantage of water storage is the high heat capacity of water, which is about five times greater than that of rock. One cubic foot of water can store 3-5 times as much heat as a cubic foot of rock. Beds of properly sized rocks, however, offer a good storage system with collectors where air is used as the heat transfer medium. Heat capacity storage is limited practically to 1 Btu/(lb)(deg. F). Storage systems utilizing the heat of fusion of salt hydrates can provide storage in excess of 100 Btu/(lb)(deg. F).

# SOLAR LUMBER DRYING LITERATURE REVIEW

A number of solar dry kilns have been built throughout the world in the last 20 years. Most of these have been relatively small experimental kilns built at universities or government research laboratories. In this report each of these kilns that has been reported in the literature, and their performance, will be described briefly. A partial bibliography of solar drying of agricultural crops is also included at the end of this report.

## Construction Details and Performance

Rehman and Chawla (1961) built a series of eight versions of a solar kiln at Dehra Dun, India (30°N). Most of the kilns used natural circulation by various arrangements of chimneys. Some of the kilns had external collectors connected to the drying chamber with ductwork. In their early designs they used conventional flat plate collectors--metal collector plates covered with glass. As their design evolved they finally decided on a simple metal box as the collector. In this final version, which they considered the most promising, the drying chamber was mounted on top of a metal box collector. A chimney on top of the drying chamber pulled air in through holes in the base of the collector up through the lumber.

In this final design the temperature in the drying chamber was 13 to 18°C above ambient. The reduction in drying time, compared to air drying, to 9 percent moisture content was 54 percent. It should be noted that these kilns were quite small, and that the load size and the size of the individual pieces were quite small.

Based on all of the kiln designs tested, Rehman and Chawla had several general observations. Little or no drying took place at night in their natural circulation designs, and in some cases the wood picked up moisture at night. No means was provided for humidifying the kiln, and some of the species, sal (Shorea robusta) and axlewood (Anogeissus latifolia), checked badly because of this inability to provide high humidity in the critical early stages of drying.

Johnson (1961) built a 400-board-foot-capacity solar kiln in Wisconsin, United States (43°N), in which the lumber was stacked at an angle to the floor. The main structure was framed with 2- by 4-inch and 2- by 6-inch lumber, and was covered with a lumber siding. The south side of the kiln was enclosed with single-pane glass storm windows giving a glass area of 37 $ft^2$, and a glazing area:lumber capacity ratio of 0.093 $ft^2$/bd. ft. The south wall was inclined at 67-1/2 degrees from the horizontal. A 3- by 6-foot collector was located directly beneath

the storm windows. It was constructed with galvanized sheet metal backed by an air space and then 1/8-inch-thick hardboard. The collector area:lumber capacity ratio was 0.045 $ft^2$/bd. ft. Circulation was provided by a four-bladed, 54-inch diameter windmill fan driving a 14-inch-diameter centrifugal fan located above the lumber. The fan drew outside air in through a slot in the floor, passed it through the collector air space, and then through the lumber. The venting capacity of the kiln was unclear. Kiln temperatures of 130° F to 140° F have been measured at 80° F to 90° F ambient, and 80° F to 90° F at 32° F ambient.

One-inch white oak was dried from 60 to 7 percent moisture content in 52 days, and 1-inch black cherry from 16 to 8 percent in about 30 days in late summer. One-inch black cherry lumber was also dried from 50 to 20 percent in 75 days, when the lumber was placed in the kiln in mid-November. An additional 125 days were required to dry the lumber to 9 percent moisture content. No mention is made of the quality of the dried lumber.

The work described by Peck (1962), Maldonado and Peck (1962), and Chudnoff, Maldonado, and Goytia (1966) is interrelated in the sense that the kilns described evolved from a first model designed by Peck at the Forest Products Laboratory, Madison, Wisconsin, U.S. The dryer designed by Peck (1962) was 7-1/2 feet wide by 12-2/3 feet long by 8 feet high. Apparently there was little or no slope to the roof. The kiln was baffled to accept approximately 425 board feet of 1-inch lumber. The walls were framed with 2- by 4-inch lumber and the roof with 2- by 6-inch lumber. Corrugated aluminum sheets (painted black on both sides) were nailed to the edges of the wall studs and the roof rafters. The roof collector area:lumber capacity was 0.224 $ft^2$/bd. ft. and the total collector area:lumber capacity was 0.51 $ft^2$/bd. ft. On all but the north wall, sheet plastic was fastened to the outer edges of the studs and rafters. A second layer of plastic was mounted on wooden frames and fastened over the first layer. Air circulation was provided by a 24-inch-diameter fan powered by a 5/8-horsepower motor. Four 8-inch-diameter vents were opened and closed by a wood element humidistat and motor. With the kiln loaded the inside temperature ranged from 9 to 22° F above ambient, depending on the time of year.

Several charges of 4/4 red oak were dried in the kiln at various times of the year. The concept of the solar kiln's purpose was that of a predryer, i.e., as a replacement for air drying to 20 percent moisture content. The results showed that, regardless of the time of year, the drying time to 20 percent moisture content was about one-half the comparable air drying time. The time to dry to 20 percent in the solar kiln was 2 to 3 times longer than in a steam-heated dry kiln using a conventional red oak schedule. The amount of surface checking that developed during drying was approximately the same in the solar kiln and in air drying.

Maldonado and Peck (1962) built and tested a solar dryer in Puerto Rico (18°N). The dryer was 10 feet wide by 14-2/3 feet long,

with a 9-3/4-foot-high south wall and a 13-1/3-foot-high north wall (16° tilt from horizontal) with a 2,000-board-foot capacity. The dryer was constructed with 2- by 4-inch and 2- by 6-inch framework. All sides but the north side were covered with two layers of polyvinyl fluoride film: a 0.001-inch inner layer and a 0.004-inch outer layer. A corrugated sheet metal collector (painted black) was located 12 inches below the inner film of the roof. The collector area:lumber capacity ratio was 0.073 $ft^2$/bd. ft. However, the clear plastic of the walls enhanced collection capacity beyond the effects of the metal collector. Four 16-inch-diameter fans powered by a 1-1/2-horsepower motor directed air past the collector and then through the lumber. A total of four vents were located in the east and west walls.

Temperatures inside the dryer averaged 28° F higher than ambient during drying; near the end of drying, when little load was imposed on the dryer, temperatures approached 40° F above ambient. A maximum temperature of 122° F was recorded in the dryer.

Two drying tests were conducted with this kiln. In one test, 1,000 board feet of 5/4 mahogany was dried (a collector area:lumber volume ratio of 0.147 $ft^2$/bd. ft.), and in another test, 2,000 board feet of 4/4 mahogany was dried (where the collector area:volume ratio is 0.073 $ft^2$/bd. ft.). Drying time was halved by solar drying compared to air drying, and the solar-dried lumber reached a moisture content lower than would be possible in air drying. A comparison of the drying times required for the two loads of lumber points out the importance of the effect of weather on the performance of a solar kiln. Even though the collector area:lumber volume ratio in the first load of lumber was double that of the second load, the first load took half again as long to accomplish the same amount of drying because considerably more rain fell during the time the first load of lumber was being dried.

Chudnoff et al. (1966) lengthened the dryer (Maldonado and Peck, 1962) to 20 feet, which increased the capacity to 3,000 board feet and reduced the collector area:capacity volume to 0.067 $ft^2$/bd. ft. The inner layer of polyvinyl fluoride failed mechanically after 1 year of service, so when the kiln was lengthened, the film was replaced with 0.002-inch polyvinyl fluoride. After 2 years' service, both inner and outer films failed, mostly due to flexing. The outer panels were then replaced with glass.

A mist sprayer was installed to reduce maximum dry bulb temperatures during the peak of the intensity of solar radiation, to reduce the wet bulb depression during this peak, and to provide a means of increasing relative humidity in order to relieve drying stress at the end of drying.

The dryer could attain a temperature 28° F above ambient. The maximum in the dryer averaged 114° F, while the maximum ambient averaged 80° F. The relative humidity in the dryer averaged about 55 percent, while the ambient averaged 76 percent. Depending upon the positioning of the

vents and whether or not the mist spray was on, the dryer could attain equilibrium moisture contents as low as 6.2 percent, or as high as 16.0 percent.

A number of full-capacity loads of mahogany were dried in this kiln. Drying time was essentially independent of the time of the year. The lumber in the solar kiln dried faster than comparable air-dried lumber, and it reached a lower moisture content (10 percent) than could be attained in air drying.

The solar-dried lumber was found to have significantly less warp than matched air-dried lumber. No difference was noticed in the degree of surface checking. A 48-hour conditioning using the mist sprayers was effective in removing casehardening.

A kiln built by Terazawa (1963) in Tokyo (36°N) appears to be the only unit reported in the literature with supplemental steam heat. The kiln was 10 feet high by 6-1/2 feet long by 6-1/2 feet wide, with a capacity of about 2,100 board feet. The framework was angle iron covered on all sides and the roof with corrugated panels of polyvinyl chloride, with no collector. A 24-inch-diameter fan powered by a 1-horsepower motor provided circulation.

The kiln was operated as a solar kiln during the daytime hours of sunny days. The steam heating system was used at night and on rainy days. Terazawa concluded that the solar kiln would be useful in drying from green to 20 percent moisture content in the summer, and from green to 30 percent moisture content in the winter if the kiln were not located in an area where cloudy days were common.

Tao and Hsiao (1964) built a solar kiln in Taichung, Taiwan (24°N) that was designed after the kiln in Puerto Rico. The kiln had a 2,500-board-foot capacity, and circulation was provided by two 18-inch fans powered by a 1/4-horsepower motor. The kiln could attain a temperature of 9° C (16° F) above ambient, and the maximum temperature noted was 115° F.

Two drying tests were reported. In one test, 1,800 board feet of 1-inch Schima (Schima superba), which is very susceptible to drying defects, was dried from 44 percent moisture content to 12 percent in 48 days in the winter. There was no direct drying time comparison with an air-dried load, but Tao and Hsiao (1964) estimated the drying to be 4 to 5 times faster in the solar kiln. No serious drying defects or casehardening were noted in the lumber at 12 percent moisture content.

For a second drying test the kiln was modified slightly. Air circulation was enhanced by increasing the fan size to 20-inch diameter and the motor to 1 horsepower. A condensation pipe was added on the north wall to help reduce relative humidity in the kiln. A coal briquet stove was also added for night heating and to help reduce the relative humidity at night. One-inch hemlock was dried from 200 percent to 12 percent moisture content in 64 days in May and June. No drying defects developed. They noted that because of the very high initial moisture content of

the lumber, the initial drying rate was very slow. The venting capacity and the condenser pipe were apparently not adequate to reduce the relative humidity sufficiently to obtain adequately fast drying rates.

Several solar kilns have been constructed in Kampala, Uganda (0° 20'N)(Plumptre, 1967; Plumptre, 1973). The first solar kiln built in Uganda (Plumptre, 1967) was of lumber frame construction covered all around by two layers (1-3/4 inches apart) of a polyester (mylar) film. The kiln was 15 by 6 by 4 feet (long axis north-south) and had a capacity of 1,400 board feet. No collector plate was incorporated, but side reflectors could be adjusted periodically throughout the day to reflect sun into the kiln. Air circulation was provided by two 18-inch fans. One vent was located on each side of the kiln.

Maximum temperatures of 130° F to 140° F were measured with ambient temperatures of approximately 80° F. Nighttime temperatures in the kiln were in the range of 80 to 90° F with 60 to 65° F ambient. These temperatures were observed during drying.

A number of drying tests were made on several species and thicknesses. Some comparisons were made with shed or covered air drying and steam-heated kiln drying. The lumber dried in the solar kiln suffered less degrade than the air-dried lumber, and was at least as good as the lumber kiln-dried in the steam-heated kiln.

It was possible to lower the moisture content of the lumber to 12 percent, lower than could be attained by air drying, but there was no significant reduction in drying time of solar drying over the shed or covered air drying. There was practically no advantage above 30 percent moisture content. Below 30 percent the lumber in the solar kiln did dry faster than the lumber air drying. The lumber in the solar kiln took 2-1/2 to 3 times longer to dry than lumber dried by a conventional schedule in the steam-heated kiln.

The second solar kiln built in Uganda (Plumptre, 1973) was essentially only larger than the first (capacity about 5,700 bd. ft.). This kiln was found to be about 10 percent slower than the first kiln. The venting capacity had been increased and, in fact, the vents were too large and had to be kept closed during drying.

The third kiln built in Uganda (Plumptre, 1973) had even more modifications. The capacity was doubled to over 10,000 board feet, apparently the largest solar lumber kiln reported in the literature. The venting was further modified to correct the under- and over-venting capacities of the first two kilns. The plastic film was changed from polyester to 0.004-inch polyvinyl fluoride for the roof and 0.002-inch for the walls. The apparent reason for the change was unavailability of the polyester film. Six 20-inch-diameter fans were powered by two 2-horsepower motors. No data on drying tests are given with the description of the second and third kilns.

A solar dryer built in Ft. Collins, Colorado (40°N)(Troxell and Mueller, 1968) is similar in design to the kilns built in Madison, Wisconsin, and Puerto Rico. Of wood frame structure, it is covered with corrugated clear fiberglass-reinforced polyester on all but the north wall. The dryer is 18 feet long by 10 feet wide with the south wall 7 feet high and the north wall 10 feet high, for a roof tilt angle of 17 degrees and a capacity of 1,200 board feet. There is no collector plate. Two 24-inch, eight-bladed fans are each powered by a 1/2-horsepower motor. Venting is provided by four 8- by 12-inch vents in the east and west walls.

The temperature capabilities of the kiln were measured both with the kiln empty and during drying. With the kiln empty, July dryer temperatures could be maintained 50 to 60° F above ambient. During drying, the temperature difference dropped to 20 to 30° F. During the night, the temperature in the dryer remained about 10° F above ambient.

One-inch-thick Engelmann spruce and lodgepole pine lumber were dried to 12 percent moisture content at different times throughout the year. At all times of the year, drying time to 12 percent was cut by one-third to one-half over air drying, and quality was not impaired.

Using measured solar radiation data the energy intercepted by the roof was used to estimate the efficiency of the solar dryer. The efficiency ranged from a low of 27 percent in February to a high of 45 percent in August.

Martinka (1969) evaluated predrying under a shed, in a low-temperature predryer, and in a solar kiln. The work was done in Kumasi, Ghana (7° N). The predryer was an unheated oven with a fan for air circulation that probably heated the chamber somewhat. The solar dryer was an 8- by 10- by 7-foot greenhouse adapted for the experiment and equipped with aluminum sheets painted black, which apparently were not covered with either glass or plastic. Air circulation was provided. No mention is made of venting capacity.

Drying tests were made on a number of species from green to 20 percent moisture content. Air drying took from 2.6 to 6.3 times longer, depending on species, than in the predryer. Air drying took from 1.5 to 3.9 times longer than solar drying, but solar drying took from 1.2 to 2 times longer than in the predryer.

A portable solar kiln was built in the Republic of the Philippines (Casin <u>et al.</u>, 1969) and evaluated in three different locations: Quezon City, Dagupan, and Laguna (all 15° N). The kiln was 7 feet wide by 5-1/2 feet long by 7-1/2 feet high, and had a 480-board-foot capacity. The roof and the east and west walls were sheathed with corrugated sheet aluminum (painted black). Roof collector area:lumber capacity ratio was 0.080 $ft^2$/bd. ft. If the side walls are included, the ratio becomes 0.276 $ft^2$/bd. ft. Sheet plastic, 0.002-inch thick, was placed over the

corrugated metal with a 6-inch air space. The north and south walls were sheathed with 1/4-inch plywood. Air could be circulated on both sides of the collector plates by one 24-inch-diameter fan driven by a 3/4-horsepower motor. Three vents, 4 by 4 inches, were located near the floor on one side of the kiln. Average temperatures inside the dryer ranged from 13° F to 21° F above ambient.

Drying tests were conducted on apitong, narra, red lauan, and tangile, and observations were made. One-inch-thick lumber could be dried in the solar kiln to a final moisture content of 7 to 10 percent in about 30 to 40 percent of the time required for air drying lumber to a final moisture content higher than could be attained in the solar kiln. Two-inch lumber could be dried to 12 percent moisture content in half the time required for air drying.

Surface checking was more pronounced in solar-dried lumber than in air-dried lumber. Regulating the vents was ineffective in preventing surface checking. Casehardening was evident in lumber air dried and solar dried, but was more severe in the solar-dried lumber.

A solar kiln modeled after the one built by Troxell and Mueller (1968) was built by Gueneau (1970) in Tananarive, Madagascar (19° S). Pine and rosewood boards and construction lumber were dried in the solar kiln, and the drying time was compared to that in a shed dryer. From green to 20 percent moisture content, the solar dryer was only slightly faster than the shed dryer. Below 20 percent, the solar kiln was considerably faster than the shed dryer. Furthermore, a final moisture content of 7 to 8 percent could be attained in the solar kiln, which is below what could be attained in air drying.

Sharma et al. (1972) constructed a wood-frame solar kiln in Dehra Dun, India (30° N). The roof and all walls but the north (covered with plywood) were covered with two layers of polyethylene film. The inner layer was 0.002 inch thick and the outer layer was 0.010 inch thick. No collector plates were incorporated. The kiln was approximately 12 feet long by 10 feet wide. The south wall was 7 feet high and the north wall was 12-1/3 feet high (27° tilt). The capacity was 1,800 board feet, and the roof area:lumber capacity was 0.07 $ft^2$/bd. ft. Circulation was provided by a 3-foot-diameter, twelve-bladed fan powered by a 1-horsepower motor. Four 10- by 10-inch vents were located on the north and south walls.

Two experimental drying runs were conducted with several species. In both experiments, drying times were compared between forced air drying, air drying, low-temperature kiln drying, and solar drying. In the first experiment it was evident that venting capacity was controlling the rate of drying in the solar kiln in the early stages of drying, because the forced air dryer was faster. In the second experiment, the venting capacity of the solar kiln was greatly increased by essentially opening one side of the kiln and operating it as a forced air dryer until the lumber reached 40 percent moisture content, and then reverting to operation as a solar kiln. This improved the performance and made the solar kiln

second only to the low-temperature dryer in reducing drying time. In all cases, the lumber could be reduced to a lower moisture content by solar drying than by air drying or forced air drying.

The quality of the solar-dried lumber was comparable to that obtained by conventional kiln drying. Casehardening was less severe in solar-dried lumber than in conventional kiln drying.

Read et al. (1974) built a solar kiln with an external collector and with heat storage capability in Griffith, New South Wales, Australia (34° S). A 600-$ft^2$ air collector, inclined 38°, is connected to the kiln by ductwork. V-corrugated collector plates are covered with a single glass cover. The three remaining sides of the collector are insulated. The collector plates are covered with a selective surface coating. The kiln is located over the heat-storage rock pile. A system of thermostats and dampers directs air as desired through the kiln or rock pile. The capacity of the kiln is about 2,700 bd. ft. and the collector area:lumber capacity ratio is 0.224 $ft^2$/bd. ft. Air circulation is provided by two 30-inch fans.

Alpine ash lumber was dried to 16 percent moisture content in the solar kiln in 20 days. Similar alpine ash required 34 days to dry to 16 percent using a combination of air drying to 29 percent moisture content and solar kiln drying from 29 percent to 16 percent.

No surface checking was noted in any of the lumber. Some collapse did occur in the lumber dried from the green in the solar kiln. Casehardening was more severe in the totally solar-dried lumber than in the lumber dried by the combination of air and solar drying.

## Economic Performance

Peck (1962) made an economic evaluation of solar drying red oak in Wisconsin. He intended the solar kiln to function as a predryer, and most of his economic analysis was a comparison of air drying and solar drying to 20 percent moisture content. Assuming certain costs charged to air drying (capital invested in yard, maintenance, etc.) and the capital tied up in the lumber, he estimated that on a year-around basis the costs of air drying and solar drying were comparable (solar drying was clearly more economical in summer, and was comparable or slightly more costly in the spring and fall).

Peck did not have the lumber graded before and after drying for a real measure of the effect of the two drying processes on the quality of the lumber, but he felt that the protection from the weather afforded by the solar kiln would restrict development of drying defects and be an additional advantage of solar drying.

Terazawa (1963) did not present an economic analysis of his solar kiln with supplemental steam heat. He did however, present comparative

steam and electric power consumptions between the solar kiln operated with supplemental steam and a totally steam-heated kiln. Steam consumption in the solar-steam kiln, in drying to 20 percent moisture content, was approximately 1,050 $kg/m^3$ of lumber in November and 300 $kg/m^3$ in August. Steam consumption in the totally steam-heated kiln was approximately 950 $kg/m^3$. Electric power consumption in the solar-steam kiln (drying to 20 percent) was approximately 120 $kWh/m^3$ of lumber in November and 70 $kWh/m^3$ in August. Power consumption in the totally-steam-heated kiln was approximately 70 $kWh/m^3$. While these energy figures do not represent a complete economic analysis, they do point to a clear advantage of solar drying in summer, but suggest that solar drying (with supplemental heat) might be uneconomical in winter.

Tao and Hsiao (1964) estimated the cost of drying (December to February) 1,800 board feet of lumber to 12 percent moisture content in their 2,500-board-foot-capacity solar kiln in Taiwan at about NT$213/1,000 bd. ft. They estimated that the cost of conventional kiln drying would have been approximately NT$567/1,000 bd. ft., and that the savings of solar drying over air drying would have been approximately NT$113/1,000 bd. ft.

Plumptre (1973) compared drying costs (in Uganda) in the 10,000-board-foot-capacity solar kiln and in an electrically heated kiln with a capacity of about 1,000 board feet. The interest cost on the investment in the kilns was not included, but the other costs were estimated at US$50/1,000 bd. ft. in the electrically heated kiln and US$30 in the solar kiln.

Read et al. (1974) compared the drying costs of a conventional steam-heated kiln with those in the solar kiln (with heat storage capacity) constructed in Australia. The cost estimate of solar drying included enough collector area to dry lumber in the same length of time as in a steam-heated kiln. The comparative drying costs were A$3.29/$m^3$ (424 bd. ft.) in a steam-heated kiln and A$3.72 in the solar kiln.

## Important Features

The solar kilns described above are all so different that it is impossible to make direct comparisons or derive exact solar kiln specifications. There are, however, a few general observations that can be made and that may be of some help in design.

An important kiln parameter is the ratio of collector area to lumber capacity. There were so many construction and other variables in each study that no quantitative evaluation is possible. Of the kilns that used indirect collection--i.e., metal collector plates--the ratio usually was 0.07 to 0.08 $ft^2$/bd. ft. However, Peck (1962) and Read et al. (1974) constructed kilns with ratios of 0.224 $ft^2$/bd. ft.

Peck (1962) and Çasin (1969) also incorporated collector plates in the walls, which raised the ratios to 0.51 and 0.28 $ft^2$/bd. ft., respectively. Of the direct collection-type kilns, the ratio of roof area:capacity ranged from 0.02 to 0.15 $ft^2$/bd. ft. When the walls of these direct collection kilns are considered, the ratio ranges up to 0.4 $ft^2$/bd. ft.

Another important kiln characteristic that can be measured is the attainable temperature rise above ambient. This is related to the drying rate of the lumber, collector size and performance, and kiln insulation. Again, however, the literature cannot supply any quantitative guidelines relating kiln design and attainable temperature rise. Further, in many cases, it was not stated whether reported temperature rises were measured on an empty kiln or during drying.

The importance of two design features does emerge from the literature. Several investigators noted little or no time advantage, compared to air drying, in the early stages of solar drying. This points out the importance of adequate venting, and the problem that can arise if large enough venting capacity is not built into the solar kilns.

The other important design feature is a source of humidification. Some investigators have noted improved quality of solar-dried lumber over air-dried lumber. Some have theorized that quality should be improved because of protection from rain and/or direct rays of the sun in some cases. However, others have noted an increase in surface checking during solar drying. This is also a species dependent observation, but it is a factor that should be considered during kiln design if refractory species are expected to be dried in the kiln. If the relative humidity cannot be kept high enough by vent control, then a source of humidification is necessary. The development of casehardening has been noted in solar kilns, and humidification is necessary to relieve these stresses after drying.

A number of glazing materials are reported in the literature. Many of the investigators reported using various plastic films. Little comment was made on their durability, possibly because results were reported before sufficient time in which to evaluate durability had passed. Chudnoff (1966) noted considerable breakdown of polyvinyl fluoride film after 2 years of service, mostly due to excessive flexing. Plumptre (1973) noted rapid disintegration of polyethylene film, but speaks favorably of polyester film.

# FEASIBILITY ESTIMATES OF SOLAR LUMBER DRYING IN DEVELOPING COUNTRIES TARGET NATION: REPUBLIC OF THE PHILIPPINES

The feasibility of using solar energy to improve the seasoning of lumber processed by small- and medium-scale operators in developing nations will be analyzed. The concept of the project has world-wide application, but to make specific estimates, a target nation--the Republic of the Philippines--was chosen. Many of the considerations in the feasibility estimate will have world-wide applicability. Those specific to the Philippines will illustrate the information necessary to complete an analysis for any country.

Some of the considerations in the feasibility estimate are qualitative, and some can be decided from the review of the literature. These qualitative considerations will be discussed first, and then the more specific and quantitative considerations will be presented.

## NEED FOR KILN CAPACITY IN THE PHILIPPINES

### Market Demands for Kiln Drying

For many end uses and secondary manufacturing processes, lumber should be dried to avoid undesirable effects such as excessive shrinkage, warping, cracking, and stain and decay caused by fungus attack. This is especially true in products such as furniture, cabinets, moldings, flooring, doors, wood carvings, and other handicrafts that will be used in temperate countries.

Air drying is useful but has some limitations related to drying defects, a slow rate of drying (up to 2 years in the Philippines), and high final moisture content in humid climates. The need for kiln capacity is based on these limitations of air drying. The literature (above) shows that a kiln can shorten drying time considerably over air drying, and that well designed solar kilns can be expected to reduce drying time by about one-half of air-drying time.

Perhaps even more important than long drying time, the final equilibrium moisture content (EMC) attainable in air drying in most areas of the Philippines is quite high. In addition to severely lengthening drying time, the high equilibrium moisture contents are too high for products that will be used in surroundings of lower EMC such as the export market to more temperate climates (particularly where homes are heated for part of the year), or air-conditioned

environments within the Philippines or other tropical climates. Average values of relative humidity and EMC (table 1) for the three major Philippine island groups (not differentiating the various microclimates within the islands) show it is not generally possible to air dry lumber much below 15 percent moisture content in the Philippines. Also, because of the extremely slow drying rate of wood as it approaches the EMC, it is probably not practical to expect lumber to air dry below 17 to 18 percent in any reasonable length of time. Moisture content levels below 10 percent are usually recommended for high quality interior uses of wood in temperate climates or in air-conditioned spaces. The chances are great that a significant percentage of wood products made from lumber above 15 percent moisture content, and then put into use in an environment with an EMC of 10 percent or less, will develop splits, distortions, ruptured gluelines, and other excessive-shrinkage related problems.

Air drying times of several commercially important Philippine species were estimated by a method that will be described in "Drying Data Input." The estimates (table 2) are for nominal 1-inch lumber at 60 percent initial moisture content. The drying times are based on the climatological data of Quezon City, for April, which is the most favorable air drying month. The drying rate becomes very slow below 30 percent moisture content, and air drying times to these lower moisture contents become quite long, even in the most favorable month of the year (table 2).

If the temperature in a drying chamber can be raised above ambient, the absolute humidity remains constant, but the relative humidity drops (table 3). This reduces the EMC, thus making it possible to dry to lower levels of moisture content. Drying rate is also increased because of the lower EMC as well as the higher temperature. On 1-inch tangile (table 4), a temperature rise of only 20° F, which should be easily attained in a solar kiln during drying, cuts the drying time at least in half at any time of the year.

The data based on real Philippine climatological data and experimentally determined estimates of the drying rates of several Philippine species (tables 1 through 4) illustrate how effective a heated dryer is in reducing both drying time and the level of final moisture content.

The desirable direction of change in the timber industry requires kiln capacity. In many countries, including the Philippines, the general practice has been to sell logs on the world market, but sound economic practice calls for instituting "value added" processes and industry, to produce for both local use and the export market. The Philippines, anxious to increase secondary manufacture of wood products, proposed a total ban of the export of logs to take effect on January 1, 1976. The ban has been relaxed somewhat and qualified timber companies can export up to 25 percent of their allowable cut (Philippine Delegation, 1975). However, the intent is to build up secondary manufacturing facilities and greater export markets for finished wood products. This desirable trend will intensify the need for dry kiln capacity as the need for more thorough drying to satisfy the export market grows.

Table 1.--Average values of relative humidity (RH) and equilibrium moisture content (EMC) in the Philippines (Philippine Weather Bureau, 1970)

| Months | Luzon | | Visayas | | Mindanao | |
| --- | --- | --- | --- | --- | --- | --- |
| | Relative humidity | Equilibrium moisture content | Relative humidity | Equilibrium moisture content | Relative humidity | Equilibrium moisture content |
| | Pct | Pct | Pct | Pct | Pct | Pct |
| January | 80 | 16 | 82 | 17 | 83 | 17 |
| February | 78 | 15 | 81 | 16 | 82 | 17 |
| March | 77 | 15 | 79 | 16 | 81 | 16 |
| April | 76 | 14 | 78 | 15 | 80 | 16 |
| May | 77 | 15 | 79 | 16 | 82 | 17 |
| June | 81 | 16 | 81 | 16 | 84 | 17 |
| July | 83 | 17 | 83 | 17 | 84 | 17 |
| August | 84 | 17 | 82 | 17 | 84 | 17 |
| September | 84 | 17 | 82 | 17 | 84 | 17 |
| October | 83 | 17 | 83 | 17 | 84 | 17 |
| November | 82 | 17 | 83 | 17 | 84 | 17 |
| December | 82 | 17 | 83 | 17 | 84 | 17 |

In discussions with the President of the Philippine Council of Furniture Manufacturers (May, 1975) it became apparent that nearly all of the 2,000 small furniture factories in the Philippines have no dry kilns, and that interest in introducing a low-cost kiln to the industry is high.

Table 2.--Estimate of air drying time of several species of 1-inch lumber at Quezon City in April (best air drying month) from 60 percent moisture content

| Species | Drying time — Final moisture content: 30 percent | 15 percent |
|---|---|---|
| | Days | Days |
| Mayapis | 12 | 39 |
| Red lauan | 10 | 34 |
| White lauan | 20 | 64 |
| Tangile | 11 | 33 |

Table 3.--Effect of temperature rise at constant absolute humidity on relative humdity (RH) and equilibrium moisture content (EMC) of wood at Quezon City

| | Temperature rise (°F) | | | | |
|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 40 |
| January | | | | | |
| Temperature (°F) | 76 | 86 | 96 | 106 | 116 |
| RH (percent) | 71 | 51 | 37 | 27 | 19 |
| EMC (percent) | 13.4 | 9.0 | 6.7 | 5.1 | 3.9 |
| April | | | | | |
| Temperature (°F) | 82 | 92 | 102 | 112 | 122 |
| RH (percent) | 71 | 62 | 45 | 32 | 24 |
| EMC (percent) | 13.2 | 10.9 | 7.7 | 5.7 | 4.5 |
| July | | | | | |
| Temperature (°F) | 80 | 90 | 100 | 110 | 120 |
| RH (percent) | 85 | 61 | 44 | 32 | 23 |
| EMC (percent) | 17.8 | 10.7 | 7.6 | 5.7 | 4.4 |
| October | | | | | |
| Temperature (°F) | 79 | 89 | 99 | 109 | 119 |
| RH (percent) | 78 | 57 | 41 | 29 | 22 |
| EMC (percent) | 15.3 | 10.0 | 7.2 | 5.3 | 4.2 |

Table 4.--Effect of temperature rise at constant absolute humidity on drying time of 1-inch tangile lumber from 60 percent moisture content at Quezon City

| Month | Final moisture content | Drying time | | | | |
|---|---|---|---|---|---|---|
| | | Temperature rise (°F) | | | | |
| | | 0 | 10 | 20 | 30 | 40 |
| | Pct | Days | Days | Days | Days | Days |
| January | 30 | 12 | 8 | 6 | 4.5 | 3.5 |
| | 20 | 23 | 14 | 10 | 7.5 | 5.8 |
| | 15 | 39 | 20 | 13 | 10 | 7.5 |
| | 10 | -- | 36 | 20 | 14 | 10.2 |
| | 5 | -- | -- | -- | -- | 18 |
| | (EMC) | (13.4) | (9.0) | (6.7) | (5.1) | (3.9) |
| April | 30 | 10.5 | 7.5 | 5.2 | 4.1 | 3.2 |
| | 20 | 19.5 | 13 | 9 | 6.8 | 5.1 |
| | 15 | 33 | 20 | 12.2 | 9 | 6.5 |
| | 10 | -- | -- | 19 | 13 | 9.2 |
| | 5 | -- | -- | -- | -- | 18 |
| | (EMC) | (13.2) | (10.9) | (7.7) | (5.7) | (4.5) |
| July | 30 | 13.5 | 8 | 5.5 | 4.1 | 3.3 |
| | 20 | 31 | 14.1 | 9.3 | 7.2 | 5.4 |
| | 15 | -- | 20.5 | 12.6 | 9.4 | 7.0 |
| | 10 | -- | -- | 20 | 13.6 | 9.7 |
| | 5 | -- | -- | -- | -- | 19 |
| | (EMC) | (17.8) | (10.7) | (7.6) | (5.7) | (4.4) |
| October | 30 | 12 | 7.9 | 5.5 | 4.4 | 3.3 |
| | 20 | 24 | 14 | 9.3 | 7.2 | 5.4 |
| | 15 | -- | 20 | 12.5 | 9.5 | 7.1 |
| | 10 | -- | -- | 9.2 | 13.5 | 9.7 |
| | 5 | -- | -- | -- | -- | 18.5 |
| | (EMC) | (15.3) | (10.0) | (7.2) | (5.3) | (4.2) |

## Philippines Climate

While the relative humidity in the Philippines is generally high (table 1), there are exceptions to the often-held viewpoint that the climate is uniformly hot and humid. The high temperatures of the tropical lowlands are not found in the highland areas. In the northern highlands of Luzon, Baguio, at 5,000 feet, has an average annual temperature of 64.2° F. The average annual temperature in the lowland areas is about 80° F. Except for the temperature differences caused by elevation, the

differences in average annual temperatures in the Philippines are so slight as to be insignificant. Seasonal variations, however, do exist.

The lowest average monthly temperatures and the largest annual ranges of temperature occur in the north. In the far north, the average January temperature of 72° F is 11 degrees less than the average of the warmest month of June. In the southernmost part of Mindanao, the coldest and warmest months differ by only 1 degree.

April through June usually constitutes summer in the Philippines. Typically these months are the warmest, dryest, sunniest, and receive the most solar radiation (table 5). The month of April is the most favorable for air or solar drying with 1,911 Btu/ft$^2$/day of solar radiation and an average temperature of 84.4° F. February is the worst month with only 1,114 Btu/ft$^2$/day at 79° F.

The greatest temperature differences are found in the diurnal (24-hour) cycle. During the dry season in Manila (April), the daily minimum is about 77° F, while the maximum is about 92° F. During the wet season (September), the daily extremes are not so large (76° F to 87° F) because of the moderating effects of the greater cloudiness.

Rainfall, which is associated with high relative humidity, is also variable by location and season. Average annual rainfall varies from a low of 35 inches in some sections of northern Luzon to 215 inches on one of the smaller islands. The seasonality of the rainfall varies, with some areas receiving summer maxima, some areas receiving winter maxima, and some receiving a fairly even distribution. The Manila-Quezon City area receives an annual average of 82 inches per year, and 57.6 inches of this falls in June through September.

The variability of the climate by season and by location influences the performance of an air-drying facility and the design and performance of a solar kiln, and will have to be considered in the feasibility estimates and the design of any drying facility.

Table 5.--Solar radiation and climatological data for Quezon City, Philippines

| Month | Average daily radiation (horizontal surface)[1] | Average monthly temperature[2] Daily maximum | Daily minimum | Daily mean | Average monthly relative humidity[2] | Average monthly rainfall[3] |
|---|---|---|---|---|---|---|
| | $Btu/ft^2/day$ | °F | °F | °F | Pct | In |
| January | 1,137 | 85.5 | 72.0 | 78.6 | 76 | 1.0 |
| February | 1,114 | 86.5 | 72.3 | 79.5 | 72 | 0.5 |
| March | 1,609 | 89.4 | 74.3 | 81.9 | 70 | 0.7 |
| April | 1,911 | 91.8 | 76.8 | 84.4 | 67 | 1.3 |
| May | 1,697 | 92.3 | 78.1 | 85.3 | 74 | 5.1 |
| June | 1,598 | 89.8 | 77.4 | 83.7 | 82 | 10.0 |
| July | 1,299 | 88.2 | 76.5 | 82.4 | 86 | 17.0 |
| August | 1,343 | 86.9 | 76.1 | 81.5 | 86 | 16.6 |
| September | 1,310 | 87.1 | 75.9 | 81.5 | 87 | 14.0 |
| October | 1,343 | 88.0 | 75.7 | 82.0 | 84 | 7.6 |
| November | 1,303 | 87.1 | 74.7 | 81.0 | 82 | 5.7 |
| December | 1,280 | 85.6 | 73.2 | 79.3 | 80 | 2.6 |
| Average | 1,413 | 88.2 | 75.3 | 81.8 | 77 | Total 82.0 |

[1] Löf, G. O. G., J. A. Duffie, and C. O. Smith. 1966. World distribution of solar radiation. Report No. 21. Solar Energy Laboratory, Univ. of Wisconsin, Madison.

[2] Philippine Weather Bureau, Climatological Division. 1970. Climatological normals (1951-1970) for the Philippines, Manila.

[3] Wernstedt, F. L., and J. E. Spencer. 1967. The Philippine Island world: A physical, cultural, and regional geography. Univ. of Calif. Press., Berkeley.

# ALTERNATIVES FOR SOLAR KILNS

## Non-Solar Kilns

Having established the need for kiln capacity for small- to medium-size woodworking plants in the Philippines, the possibility of alternative types of dry kilns should be examined. One alternative is the "conventional" steam-heated or direct-fired dry kilns offered by kiln manufacturers throughout the world. These kilns generally have instrumentation to control and record wet- and dry-bulb temperatures. They represent the state-of-the-art in lumber dry kiln technology and degree of sophistication. The well designed and well built kilns of this type are capable of relatively rapid and quality lumber drying. No thorough, world-wide analysis of capital costs for these kilns was attempted for this feasibility estimate. However, the current cost of a hardwood lumber kiln in the United States is approximately $2 per board foot of holding capacity for a 30,000-board-foot kiln. The cost of a kiln per board foot of holding capacity rises as capacity falls because certain cost elements are independent of kiln size. A 10,000-board-foot kiln, comparable otherwise to the 30,000-board-foot kiln, would cost $4 per board foot of holding capacity.

The need for low-cost kiln capacity in the Philippines has driven some wood product manufacturers to construct furnace-type dry kilns. These kilns are basically ovens heated by burning wood residues, with no provision for positive control of relative humidity. One kiln of this type is shown in figure 1. It is a wood-waste incinerator converted to a kiln of about 1,500-board-foot capacity. The drying chamber is in the upper part of the incinerator, and is separated from the fire box by a floor and layer of sand. A small fan in the drying chamber provides circulation. No cost or performance data were available for this kiln, other than the fact that the plant owner considered it essential in his operation in order to prevent a recurrence of export-market rejects he has had in the past. This plant situation also illustrates the importance of a properly sized drying facility. Before the need for kiln capacity was recognized, the plant produced 800 high quality doors per month. Because the undersized kiln bottlenecks production, the plant is now limited to producing only 300 doors per month.

Another type of low-cost furnace kiln was introduced in the Manila area in early 1975. These kilns are of concrete block construction, with a plywood sheathing roof insulated with coconut fiber. A fire box is located at the rear of the kiln. One wall of the fire box is a thick steel plate, 5 to 6 feet square, to serve as a heat transfer medium between the fire box and the kiln. A 6-foot-diameter fan is located in front of this plate. The drying chamber and load are arranged so that after each pass through the wood the circulating air is either directly impinged (90 degrees) upon the heated plate, or, upon fan reversal, flows across the plate in a turbulent manner. Manually controlled venting is provided in an attempt to maintain the desired wet-bulb temperature. Maximum dry-bulb temperatures are 140 to 150° F.

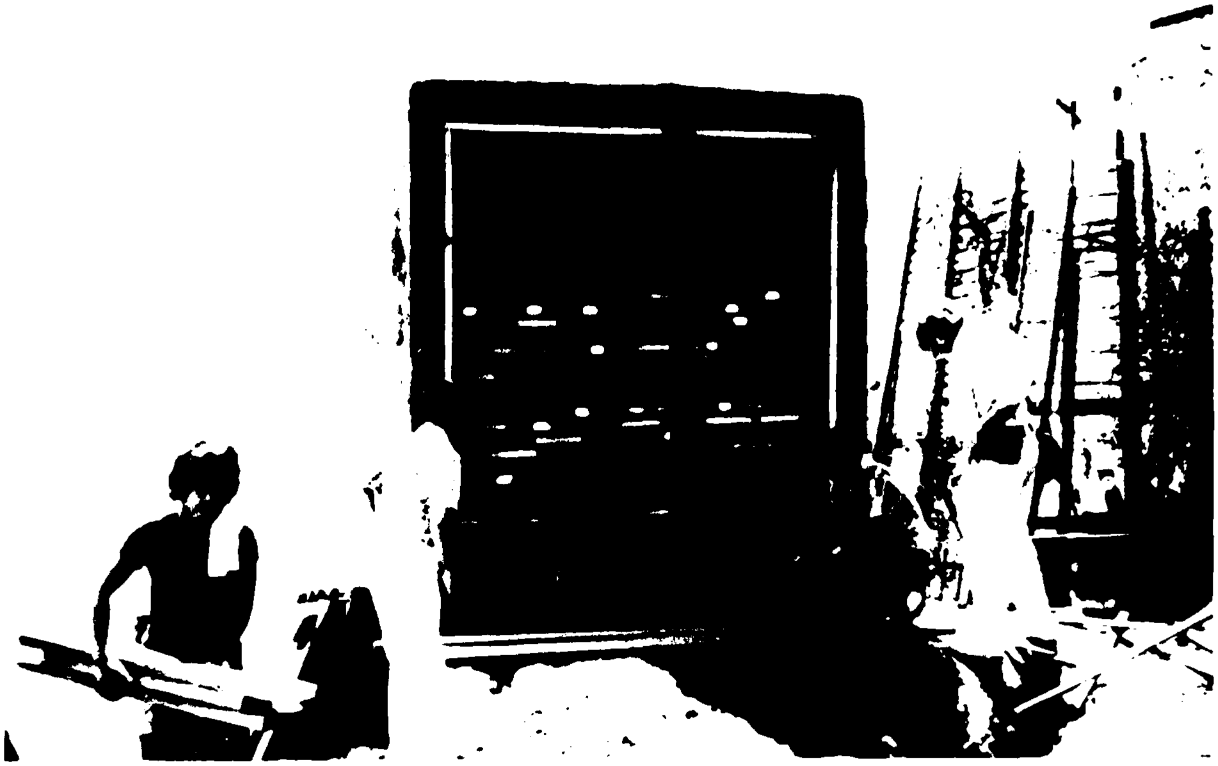

Figure 1.--Furnace-type dry kiln in use in the Philippines (May, 1975).
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The kilns are intended to be hand-fired by wood waste. The reported cost of a 20,000-board-foot kiln of this design is approximately $4,000 to $4,500. Another 10,000-board-foot capacity kiln of this same general type was reported to cost $3,600. The suitability of these kilns is subject to the competition of other uses for wood waste. No performance data are available on this version of a furnace kiln because it is so new. A critical limitation is the lack of a source of humidity beyond the control available by closing the vents. If this lack of humidity causes the development of surface checks in the early stages of drying, and if casehardening stresses cannot be relieved without a source of humidity, the kiln may not be satisfactory for drying high quality furniture wood.

The furnace kilns meet the low cost criteria, and, from some limited drying time data gathered, it appears that they can meet the production rate requirements. The design of this kiln raises certain questions on how well it will perform. The uniformity of air circulation is questionable, and the lack of humidification may well be a serious fault. Casin et al. (1969) have concluded that humidification is necessary on some of the important Philippine species to prevent surface checking during drying, and to relieve casehardening stresses after drying. A further possible limitation of the furnace-type kiln is the availability of wood waste and the competition of other uses

for wood waste. In some areas of the Philippines, wood waste is readily available and has no competitive use. In other areas, wood waste has domestic uses that would be considered more important than lumber drying. Even in areas where wood waste is now readily available, the potential always exists that the markets will change and cause competition for wood waste. Therefore, even though the furnace-type kilns seem to have potential, their possible performance limitations and the sensitivity of the availability of wood waste to changing markets suggest that other low-cost kiln designs be explored as possible alternatives to the furnace-type kilns.

### Alternative Methods of Operating a Solar Kiln

One such alternative is a solar kiln with a back-up heating system for night or cloudy-day operation. A combination solar and furnace-type kiln could offer a fairly low-cost system, reduced dependence on the availability of wood waste, and 24-hour-a-day operation, but at the cost of two energy transfer systems where one system might not be useful if wood waste were to become expensive or unavailable.

A solar kiln can be operated in several different ways. It can be operated as a predryer for the purpose of improving upon air drying with final drying from the air dry condition to final moisture content done in a conventional dry kiln. This would only have application where conventional dry kilns are available. A solar kiln could be used to dry all the way from the green condition to final moisture content, or it could be used for final drying following air drying to some intermediate moisture content. The design of a solar dry kiln will be dependent on the intended method of operation.

## DESIGN CONSTRAINTS AND FEATURES

### Design Constraints in the Philippines

The intention of the discussion so far has been to present some of the reasons kiln capacity is needed in the Philippines and some of the alternatives available. Some specific factors need to be evaluated before alternatives can be eliminated and kiln design features be selected.

#### Cost

The major design constraint for a kiln suitable for small- to medium-size woodworking plants in the Philippines is cost. That factor was understood from the beginning, but only by discussions with Philippine

industry representatives and others familiar with the industry could "low cost" be quantified. A low-cost dry kiln was defined as one costing approximately from $3,000 to $5,000. This constraint virtually eliminates a "conventional" factory-built dry kiln. A 10,000-board-foot kiln of this type would cost $40,000, perhaps more considering that it would have to be imported. A kiln smaller than 10,000 board feet would cost more than $4 per board foot. Even if the cost only rose to $5 per board foot, $5,000 would only purchase a 1,000-board-foot kiln.

Collector.--In considering design possibilities for a solar kiln the cost of prefabricated collectors offered for sale by solar manufacturers should be considered. Prefabricated glass collectors generally range from approximately $10 to $15 per square foot of collector surface, which would make a solar kiln equipped with such collectors quite expensive.

There is a wide range of cover materials with a correspondingly wide range of cost and performance available as glazing for solar collectors. Polyethylene and polyvinyl chloride are two low-cost, nonrigid plastic film materials. Polyethylene 0.004 inch thick sold in 1975 for $.0117 per square foot in the Philippines. Polyvinyl chloride sold for $.024, $.037, and $.098 per square foot for 0.004, 0.006, and 0.016 inch thick in the Philippines. Mylar (a polyester) and Tedlar (polyvinyl fluoride) are higher strength, more durable, nonrigid film materials that have been used for solar collector glazing. Mylar in 1975 cost $.278 per square foot in the Philippines. Tedlar (0.004 inch thick) sold for $.25 per square foot in the United States.

Rigid, thicker glazing materials are also available. Ordinary window glass for solar collection use cost $.43 and $.77 per square foot in the Philippines for 1/8- and 3/16-inch-thick material. Fiberglass reinforced polyester panels are available in the thickness range of 0.040 to 0.060 inch, which is thick enough to give the panels some rigidity, at least against the action of the wind. Panels especially formulated for high solar energy transmission and good resistance to degradation from ultraviolet light are available. Glazing of this type is available in the United States at prices ranging from $.50 to $.75 per square foot and some prefabricated panels are available at under $2 per square foot.

Storage.--Storage of solar energy for night use should also be considered in the feasibility estimate. No detailed analysis of the costs of alternative storage media was attempted because the practicalities of adapting solar energy to a low-cost lumber kiln narrow the selection to either rock or earth. Salt hydrates are certainly more expensive than water, rock, or earth. It would be impractical to use water storage with air collectors because of the extra heat transfer hardware involved. Similarly, it would be impractical to use liquid collectors because they also would require extra heat transfer hardware between

the heated liquid and the heated air to be forced through the stacked lumber. Rock or earth storage can be incorporated in an air system with minimum expense.

Casin et al. (1969) also found that the solar-dried Philippine species all had casehardening stresses after drying. A high humidity conditioning period in the kiln is necessary to relieve these stresses, which cause distortions in the lumber in subsequent machining operations. In conventional steam-heated dry kilns, stress relief conditioning is usually done at temperatures of 170° F or greater, and at relative humidities of approximately 80 percent. It is unlikely that a temperature of 170° F is attainable in a low-cost kiln using flat plate collectors. Conditioning would therefore have to be done at lower temperatures. The effectiveness of low temperature stress relief is not well defined. Stress relief is dependent upon temperature, relative humidity, and time. If stress relief is attempted at lower temperatures than usual (170° F to 180° F), then either relative humidity or time or both have to be increased to accomplish adequate stress relief. Churchill (1954) showed that stress relief is possible at lower temperatures, but he did not devise any definite procedures. The approach to this problem in testing the feasibility and in designing a low-cost solar kiln will have to be that lower temperature (below 150° F) stress relief is possible, and therefore, that provisions for humidification be planned, but the exact procedures (time, temperature, relative humidity, and species) will have to be developed after the solar kiln is put into operation.

## Collector ratio

The ratio of the collector area of a solar kiln to the capacity of the kiln is certainly an important factor in the performance of a solar kiln. Too small a ratio will result in excessively long drying times. Too large a ratio could result in excessive construction costs that would have minimum effect on increasing the performance of the kiln. In the early stages of drying, energy collection will often be the rate-controlling step because of the relatively high energy demands when drying rate is fast. Later in the drying process, drying rate decreases as the moisture content of the wood falls, and it is quite likely that drying rate rather than energy collection becomes the rate-controlling step. There are no quantitative guidelines in the literature to aid in designing for the optimum ratio. Two alternative general designs have an effect on the ratio of collector area to capacity that is attainable. If the collector is an integral part of the solar kiln, the ratio is limited (for practical reasons) by the geometry of the kiln. The ratio can be made considerably larger with an external collector.

## Size

Another design constraint is the production rate of small- to medium-size woodworking operations in the Philippines. Discussions with individuals familar with the Philippine woodworking industry established the lumber consumption of the typical small- to medium-size operator at approximately 1,000 to 3,000 board feet per week.

## Utilities

The availability of water and electricity is another design constraint. Water will be necessary if humidification is to be incorporated in a kiln (Casin et al., 1969). Electricity would be necessary for any fans or blowers, and humidistats and humidifiers. In some rural areas, water and electricity are unavailable. In cities--for example, the Manila area--they are generally available. Also, there is a concentration of woodworking plants around larger cities, particularly Manila.

## Design Features of a Low-Cost Solar Kiln

The design constraint of a \$3,000 to \$5,000 capital cost for a dry kiln dictates a relatively low level of sophistication in the kiln design. The approach to the solar kiln design and feasibility estimates was to establish minimum performance requirements for a solar kiln and then estimate the cost of construction of a kiln that will meet these requirements and determine if it falls within the cost boundaries that have been established.

The literature review has pointed out some general design features that should be considered. Analysis at the U.S. Forest Products Laboratory, as part of this research project, has pointed out other design features.

## Humidification

According to Casin et al. (1969), a positive source of humidification (in addition to vent control) will be required in solar drying certain Philippine species. During the heat of the day, the temperature in a solar kiln will rise and the relative humidity will fall, causing drying conditions in the early stages of drying that Casin found were too severe for apitong, tangile, red lauan, and narra--all commercially important Philippine species. Surface checks were observed in all of these species.

### Circulation

Some attempts have been made to incorporate natural air circulation in a solar kiln. However, no proven design has emerged. There is considerable application for solar kilns in areas where electricity is available, so it seems advisable to work toward designs that will incorporate forced circulation with electrically driven fans.

### Cover material

There is evidence in the literature that the thin (0.001 to 0.010 inch), highly flexible, plastic films are not durable in solar applications. Film degradation from ultraviolet radiation and flexing in the wind severely shortens film life. In considering designs for the Philippines the occurrence of high winds (typhoons) must be assumed, and thicker, more rigid glazing materials will be necessary.

# SOLAR DRY KILN DESIGN OPTIMIZATION BY COMPUTER MODELING

By the mid-60's the Forest Service had generated world-wide interest in the use of solar energy for drying of lumber. The work of Peck, Troxell and Mueller, Chudnoff, and others in one way or another had demonstrated that solar energy could be transformed into useful thermal energy in which state it could be used to dry lumber. Since that time there have been many additional studies principally in laboratories in other parts of the world. These were reviewed in another part of this report.

In the late 60's, the Forest Products Laboratory took another look at the applications of solar energy for the drying of wood. It was felt that perhaps these earlier studies had merely been performance studies of particular designs or inventions, contributing only demonstrated potential rather than real economic advantage. It seemed appropriate to evaluate solar drying using a broader approach wherein many designs in many climatic situations could be contrasted. Therefore, as a preliminary planning and engineering design approach, it was concluded that computer modeling would more economically generate additional information than a continuation of experimental R & D activity. The initial engineering study resulted in a computer program capable of exploring the merits of supplemental solar drying, a combination of solar and conventional fuels as an energy source in the dryer. This computer model attempted to estimate the feasibility of supplemental solar energy as a possible method for reducing drying fuel costs. This program was not immediately applicable to the

unsteady-state conditions of a cyclic solar dryer (100 percent solar energy) wherein conditions of temperature and humidity (and therefore, rates of drying) were constantly changing over a diurnal period, but was adapted.

## DRYING DATA INPUT

Drying data are either lacking or unavailable, for various woods, in analytical form as a function of wood species, density, initial moisture content, board thickness, temperature, relative humidity, and air velocity. These data are necessary input to the computer program. The strategy of this study was to use a local species readily available to find the simplest equation, theoretical, semiempirical, or empirical, that would with reasonable precision express the wood drying rate as a function of temperature, relative humidity, and thickness. Twelve drying experiments were performed on a commercial grouping of northern red oak. A simple mathematical expression was found (semiempirical) to correlate these data. It was experimentally shown that cyclic drying rates (unsteady-state) could be adequately predicted from drying rates of fixed (steady-state) conditions. The drying rates were measured at the Forest Products Laboratory for 43 Philippine wood species from the green condition and were correlated by the same semiempirical equations which made it possible to estimate the drying rate for Philippine species at all conditions and thicknesses by comparison to the detailed study of red oak. For lack of time (manpower) it was not possible to specifically model in a sophisticated manner the unsteady-state solar dryer (100 percent solar energy); however, the aforementioned program was modified slightly to yield engineering estimates of solar dryer size, orientation, materials of construction, and production rates.

### Drying Rates of Red Oak

#### Materials and preparation

Fresh, green, northern red oak logs, 9 feet long and 16 inches in diameter, were purchased from a commercial mill within 30 miles of Madison, Wisconsin, U.S., as mixed species of the red oak group. Moisture content was 85 percent and specific gravity was 0.56.

For rate of drying at constant thickness (1 inch), sufficient boards were prepared for the 10 planned experiments. The specimen size was in all cases 6 x 44 x 1 inch, flat sawn. The logs were numbered and flat sawn with the board position in the log identified. All of the recovered boards were machined to thickness, ripped to width, and cut into two lengths of clear wood, identified with log number, position, and butt or top of log. These in turn were distributed between the 10 experiments by an "incomplete" random block design. All 10 groups were tightly wrapped in plastic and sealed and stored frozen at 5° F. Each bag of 20 boards was randomly assigned to one of the experimental groupings.

## Experimental procedure

A total of 11 experiments on red oak were performed: nine at various temperatures and humidities (120°, 150°, and 180° F at 20, 50, and 80 pct relative humidity; 1-inch thickness); one under cyclic conditions (1-inch thickness); and the last on various board thicknesses (one set of drying conditions). Each experiment consisted of 20 experimental boards plus 4 dummy (green) or end-effect boards at the top and bottom of each stack. The boards were piled, one upon the other, in random order, stickered (3/4 inch) such that the package was 12 boards high and 88 inches wide (figure 2). For all experiments air velocity was 500 to 600 feet per minute.

The drying equipment used was fairly typical laboratory-size kilns, 1,500-board-foot capacity, adapted (with baffling) to these small differential experimental loadings. In addition, cyclic drying conditions were considered in experiment No. 10. The material was 1-inch red oak identical to that used in experiments 1-9; conditions were constantly variable.

Another experiment, No. 11, at fixed drying conditions of 150° F and 50 percent relative humidity used a mix of red oak boards of three machined thicknesses, 1, 1-1/2, and 2 inches, to establish a quantitative effect of thickness on drying rate.

The drying rate was experimentally determined by weighing each board initially and at increasing intervals until all boards approached equilibrium conditions for the temperature and humidity in the dryer. All the boards were removed from the dryer, and a gravimetric determination of the dry weight of each board was *established* by conventional methods (105° C, constant weight). All data were transferred to computer cards for rapid data reduction and subsequent correlation.

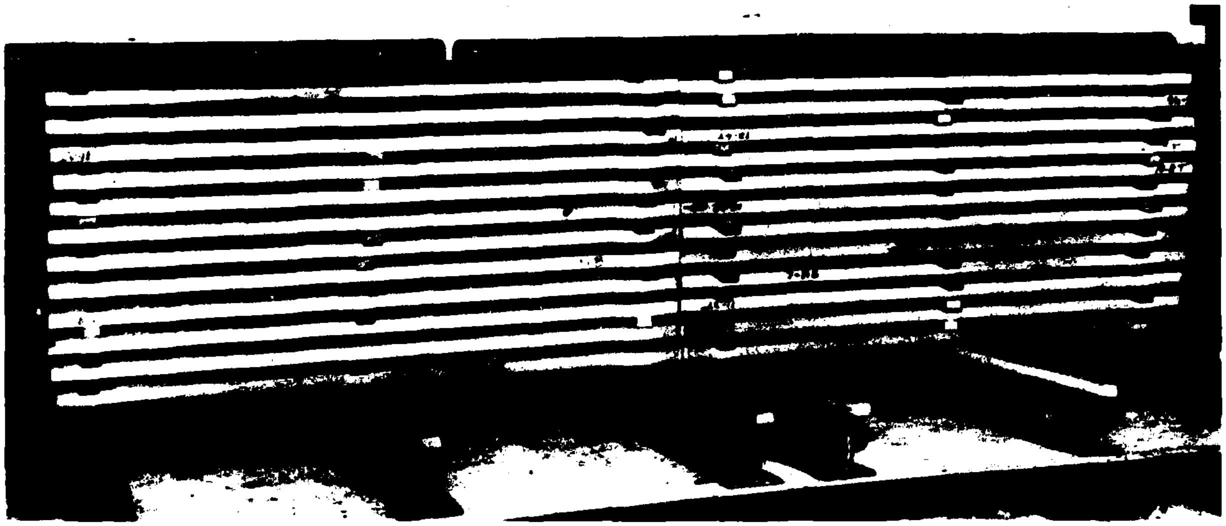

**Figure 2.--Typical stacking of red oak in drying studies.
M 143 960-12**

Correlation of red oak
drying rates

No interest or attempt at establishing mechanisms of wood drying was implied in the beginning of the experimental study. The only direction herein has been to find an analytical function to define drying times at different temperatures, relative humidities, board thicknesses, and wood species to be used mainly for interpolation in computer modeling.

One very simple but useful approach used for many years in drying studies for purpose of dryer design has been the assumption that the rate of drying is proportional to the average moisture content. This can be expressed as:

$$\frac{d\overline{W}}{d\theta} = - K\overline{W}$$

$$\int_{W_o}^{W} \frac{d\overline{W}}{\overline{W}} = - \int_{\theta=0}^{\theta} K d\theta$$

$$\ell n \frac{\overline{W}}{W_o} = - K\theta$$

$$\frac{\overline{W}}{W_o} = \exp(-K\theta)$$

Defining E as unaccomplished moisture change:

$$E = \frac{\overline{W} - W_e}{W_o - W_e}$$

where $W_e$ = equilibrium moisture content (EMC),

$\overline{W}$ = average moisture content at time $\theta$, and

$W_o$ = initial moisture content

Thus,

$$E = \frac{\overline{W} - W_e}{W_o - W_e} = \exp(-K'\theta) \qquad (1)$$

where $\theta$ = time, and

$K'$ = empirical constant, a function of wood species, temperature, and board thickness and shape.

In general, no constant rate period was detected in these wood drying studies, i.e., a falling rate period is the only regime observed. Also, for the most part, at low drying rates for wood, the rate of drying is controlled by an internal "diffusion" mechanism, and therefore, for a differential bed, would be independent of air velocity between the boards. Fortunately, for the needs of this study, Equation 1 was found to be adequate for the correlation of the drying rate of red oak. The equation was used in the following form:

$$E = \frac{\overline{W} - W_e}{W_o - W_e} = \exp(-f_s b\theta/\ell^n) \qquad (2)$$

where: $f_s$ = factor relating relative ease of drying of any species (s) to red oak ($f_s = b_s/b$ where $b_s$ = empirical constant for any species),

$b$ = empirical constant, experimentally established for red oak,

$\theta$ = time (days),

$\ell$ = board thickness (in.), and

$n$ = empirical thickness coefficient.

For red oak, values of b were obtained by regression analysis, using all 20 boards (table 6).

Table 6.--Drying rate coefficient b at different temperatures and relative humidities, red oak

| Temperature[1] | b | | |
|---|---|---|---|
| | Relative humidity[1] | | |
| | 20 percent | 50 percent | 80 percent |
| °F | | | |
| 120 | 0.2023<br>(121°, 17%) | 0.2186<br>(120°, 45%) | 0.2059<br>(122°, 61%) |
| 150 | 0.3081<br>(152°, 18%) | 0.4197<br>(156°, 38%) | 0.3857<br>(152°, 74%) |
| 180 | 0.6039<br>(182°, 20%) | 0.6174<br>(180°, 44%) | 0.5307<br>(177°, 77%) |

[1] Actual values for each experiment are in parentheses.

At this point, the thickness coefficient was not established; however, because $\ell = 1$ inch, then $\ell^n = 1$; for red oak, $b_s = b$, therefore $f_s = 1$. Then the equation used for fit is simply:

$$E = e^{-b\theta}$$

Because the experimental values of b fell only in the range of 120° F to 180° F, it was desirable to find a way of extrapolating the b's to lower (and higher) temperatures. In addition, if an analytical form could be found, computer modeling would be simplified to provide both interpolation and extrapolation. The following plots of b = f(t) were reviewed: b vs. t, $\ell n$ b vs. t, $\ell n$ b vs. 1/T. None of these graphs were linear. In addition b was plotted against vapor pressure of water. While not linear, this last plot permits extrapolation to lower temperatures, with the assumption that b = 0 at p = o (figure 3). No further attempt at establishing an empirical function was made. For computer programming, a linear interpolation of a table of values was used (b vs. vapor pressure in table 7).

## Cyclic drying

Cylic drying conditions (unsteady-state) are the mode of operation of a solar kiln. Because a programmable dry kiln was available at the Forest Products Laboratory, it was possible to establish cyclic drying

Table 7.--Drying rate coefficient b for red oak at various temperatures

| Temperature | b[1] | b[2] | |
|---|---|---|---|
| °F | | | |
| 70 | 0.093 | 0.060 | Ex.[3] |
| 80 | .118 | .075 | Ex. |
| 90 | .134 | .095 | Ex. |
| 100 | .150 | .125 | Ex. |
| 110 | .160 | .150 | Ex. |
| 120 | .180 | .190 | In. |
| 130 | .195 | .235 | In. |
| 140 | .238 | .290 | In. |
| 150 | .280 | .350 | In. |
| 160 | .355 | .425 | In. |
| 170 | .460 | .505 | In. |
| 180 | .620 | .600 | In. |
| 190 | .900 | .715 | Ex. |

[1] From $\ell n$ b vs. 1/temperature.
[2] From b vs. vapor pressure of water.
[3] Ex. = extrapolated. In. = interpolated.

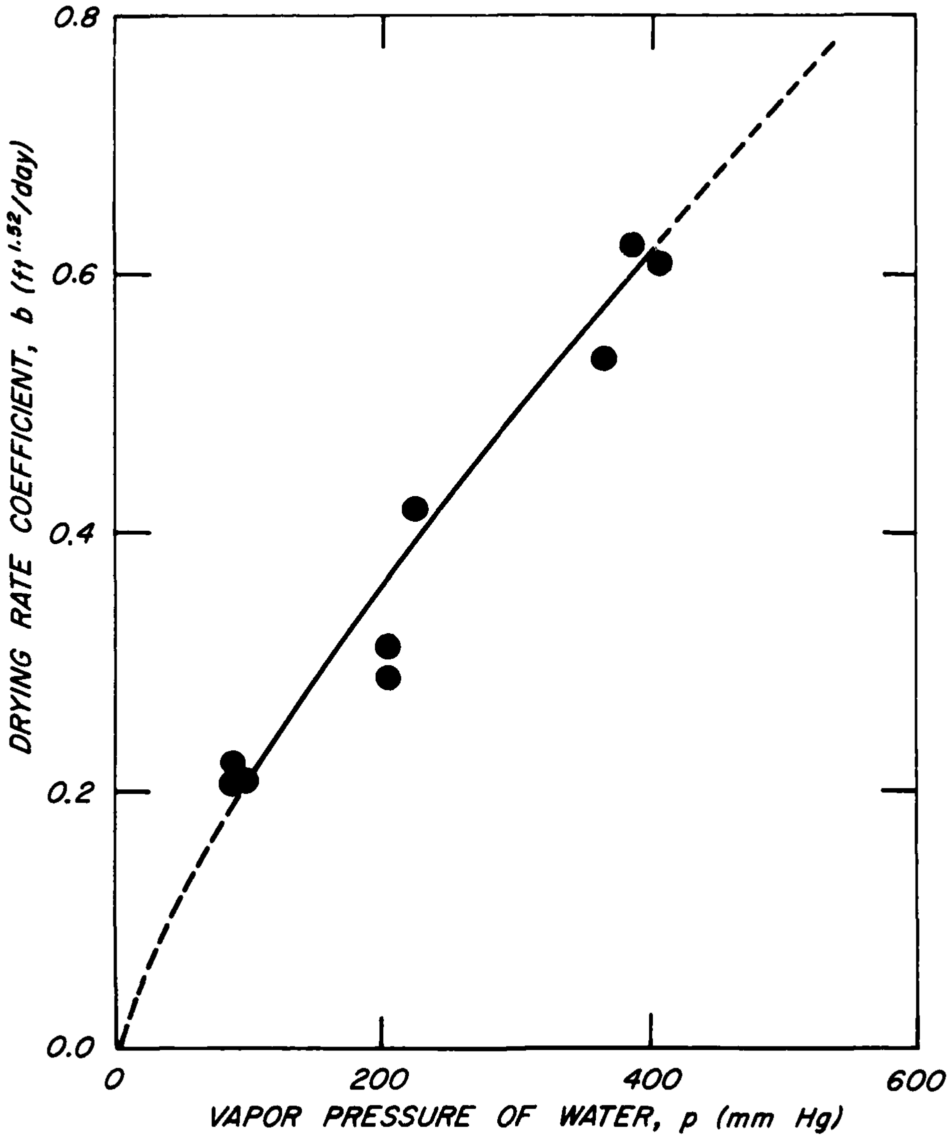


Figure 3.--Dependence of red oak drying rate coefficient b on vapor pressure.
M 144 785

conditions for a drying rate experiment. In Experiment No. 10, cyclic conditions of temperature and relative humidity were obtained on a repeating diurnal basis. The actual levels of temperature and humidity were taken from experimental performance data of a greenhouse-type solar kiln located in Puerto Rico (table 8)(Chudnoff et al., 1966). The average moisture content from the green after 52 days of this diurnal cycle was 6.95 percent. It is interesting to observe that this final moisture content is lower than the average EMC of 8.7 percent for the cyclic day. By outward appearances, the quality of the cyclically dried red oak was very good, i.e., a minimum of checks, splits, warp, and honeycomb.

Table 8.--Temperature and relative humidity levels from experimental performance of a greenhouse-type solar kiln in Puerto Rico (Chudnoff *et al.*, 1966)

| Time | Temperature | Relative humidity | Equilibrium moisture content |
|---|---|---|---|
| Hr. | °F | Pct | Pct |
| 2 | 86 | 66 | 11.3 |
| 4 | 84 | 66 | 11.2 |
| 6 | 82 | 62 | 11.0 |
| 8 | 83 | 65 | 11.7 |
| 10 | 102 | 41 | 7.1 |
| 12 | 114 | 32 | 5.6 |
| 14 | 124 | 24 | 4.4 |
| 16 | 128 | 20 | 3.7 |
| 18 | 114 | 36 | 6.2 |
| 20 | 100 | 56 | 9.6 |
| 22 | 92 | 66 | 11.5 |
| 24 | 88 | 60 | 10.7 |
| | $\overline{t} = \overline{100}$° F | $\overline{RH} = \overline{50}$% | $\overline{EMC} = \overline{8.7}$% |

The problem of casehardening was reconfirmed in this experiment (figure 4) pointing out the need for concern and correction in future dryer design, particularly for susceptible woods.

For complete modeling of a solar kiln, a quantitative representation of the unsteady-state (cyclic conditions) drying rate must be available in some form. A simple numerical computer program incorporating the b values from table 7 was written to test the feasibility of this approach in establishing the rate of drying of red oak under simulated solar conditions. This numerical solution (computer estimate) using 1-hour time increments (stepsize) was found to give a fairly good estimate of moisture content with time (table 9). The success found in applying these drying coefficients for the computation of the unsteady-state cyclic drying conditions (solar kilns without supplemental heating) was encouraging. Within the dimensions of this AID contract, it was not possible to use this analysis; however, future computations in the development of a solar kiln model will incorporate this program as a subroutine.

Thickness coefficient, n

The establishment of the thickness coefficient, n, was experimentally accomplished as an estimate by drying under one set of conditions (150° F, 50 percent RH), machined boards, 6 x 44 inch x ℓ (Experiment No. 11):

Table 9.--Comparison of experimental and calculated values of moisture content during cyclic drying conditions

| Time | Moisture content | |
|---|---|---|
| | Experimental | Calculated |
| Days | Pct | Pct |
| 0 | 85.0 | 85 |
| 5 | 40.2 | 46.2 |
| 10 | 25.9 | 25.9 |
| 15 | 18.5 | 16.5 |
| 20 | 13.9 | 12.1 |
| 25 | 11.3 | 9.9 |
| 30 | 9.2 | 8.6 |
| 35 | 8.4 | -- |
| 40 | 8.2 | -- |
| 50 | 7.4 | -- |

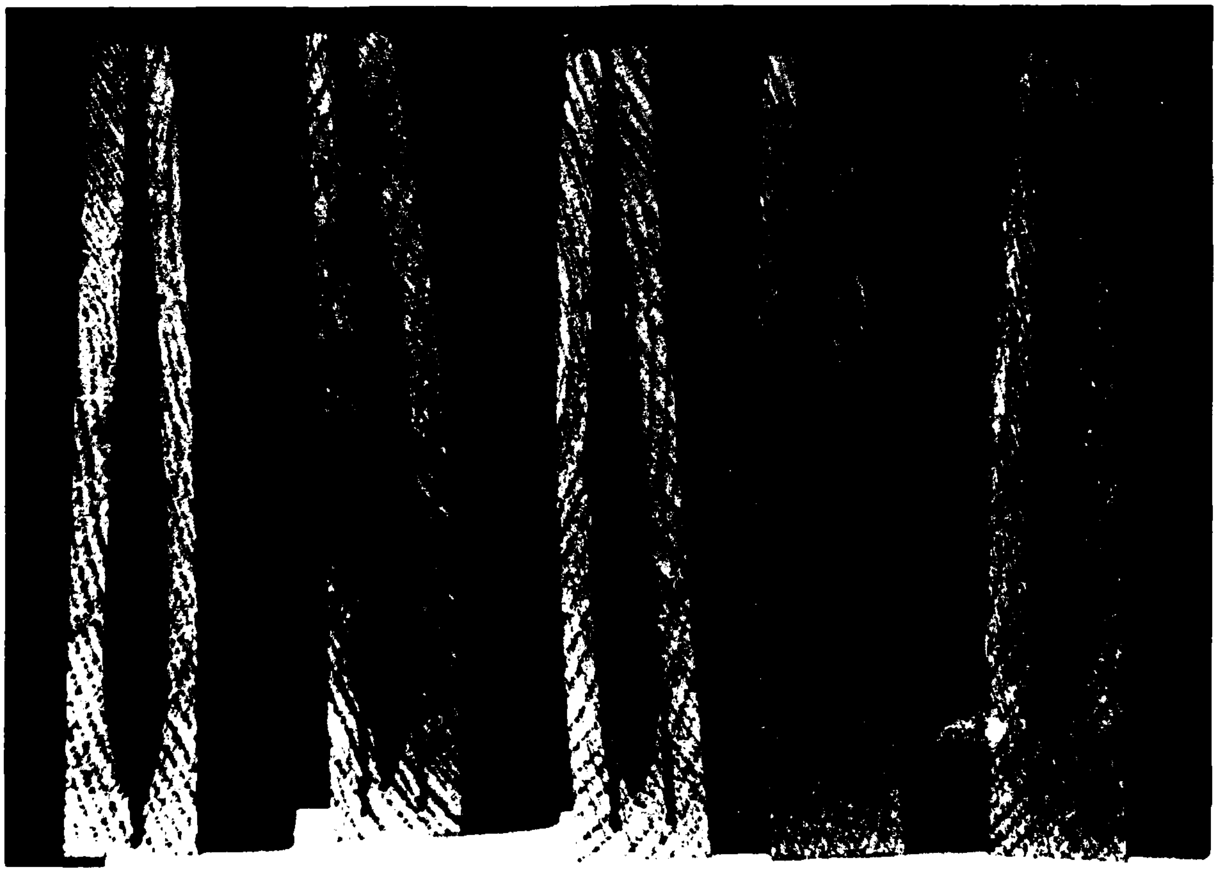

**Figure 4.--Casehardening in red oak after drying by a diurnal temperature and humidity cycle typical of a solar kiln.**
M 144 774-16

| $\ell$ in. | Number of boards |
|---|---|
| 1 | 11 |
| 1-1/2 | 14 |
| 2 | 16 |

The data were interpreted graphically and the constants obtained were:

$$b = 0.2939 \text{ at } 150° \text{ F, } 50\% \text{ RH} \quad \ell = 1 \text{ inch}$$
$$n = 1.457 \ (\ell = 1\text{-}1/2)$$
$$n = 1.585 \ (\ell = 2)$$
$$\bar{n} = 1.52$$

While the data are limited, the value of n = 1.52 is perhaps a better estimate than n = 2 which was used in the absence of any experimental data. There is no justification for assuming that the empirical coefficient n would be the same for all woods under all conditions, but, for lack of any additional data, the value n = 1.52 was used not only for the red oak drying rates, but also for the interpretation of the drying rate data of all of the Philippine woods.

## Relative Drying Rates of Philippine Woods and Red Oak

The rate of drying of wood is dependent upon the properties of the drying medium (air), as well as of the wood species. Wood properties such as density, permeability (capillary flow), and diffusion coefficients are all species-dependent and, even if known, cannot predict the drying rate behavior of a given species in any practical manner. In addition, wood as a natural material has exaggerated anisotropic properties related to the biology of its formation. Therefore, it is not surprising that tangential, radial, and longitudinal surfaces dry at different rates. Board thicknesses, shape, and position in the log are important. In addition, the relative proportions of sapwood and heartwood must be considered. Superimposed upon this are natural variations in the wood caused by age, genetics, and environmental effects all subject to modification by certain pathological states, e.g., wetwood. The practical approach to drying of temperate woods has been the development of kiln schedules as a compromise between rapid drying and degrade (loss of wood value). The commercial practice in the drying of tropical woods is an extension of the same technology. If any generalization can be made in contrasting tropical and temperate woods, it is that the former are more difficult to dry in the sense of greater propensity to degrade.

An overture was made (with suggested transfer of funds) to FORPRIDECOM to perform some drying measurements similar to the red oak experiment at FPL. Apparently this service work could not be done at that time (July 1975). In the early summer of 1975, green Philippine wood of varying densities was shipped (air freight) to FPL in Madison, Wis., U.S. from Manila, for the AID study on utilization of secondary hardwoods.

Samples from this material were used to provide crude estimates of drying rates.

## Material and conditions

Because the logs were obtained for pulping, their diameters averaged only about 12 inches. Drying specimens (total 83; 43 species) were diameter-cut through the pith, board thickness ranging from 1 to 1-1/2 inches. The boards were all about 15 inches long, rough sawn, bark removed, containing both heartwood and sapwood. All the end grain (two ends) was covered with an asphalt-type end coating.

The material was dried in two steps: green to 14.1 percent (120° F, 80% RH) and 14.1 to 7.2 percent (120° F, 43% RH). All of the boards were at equilibrium at the end of each step.

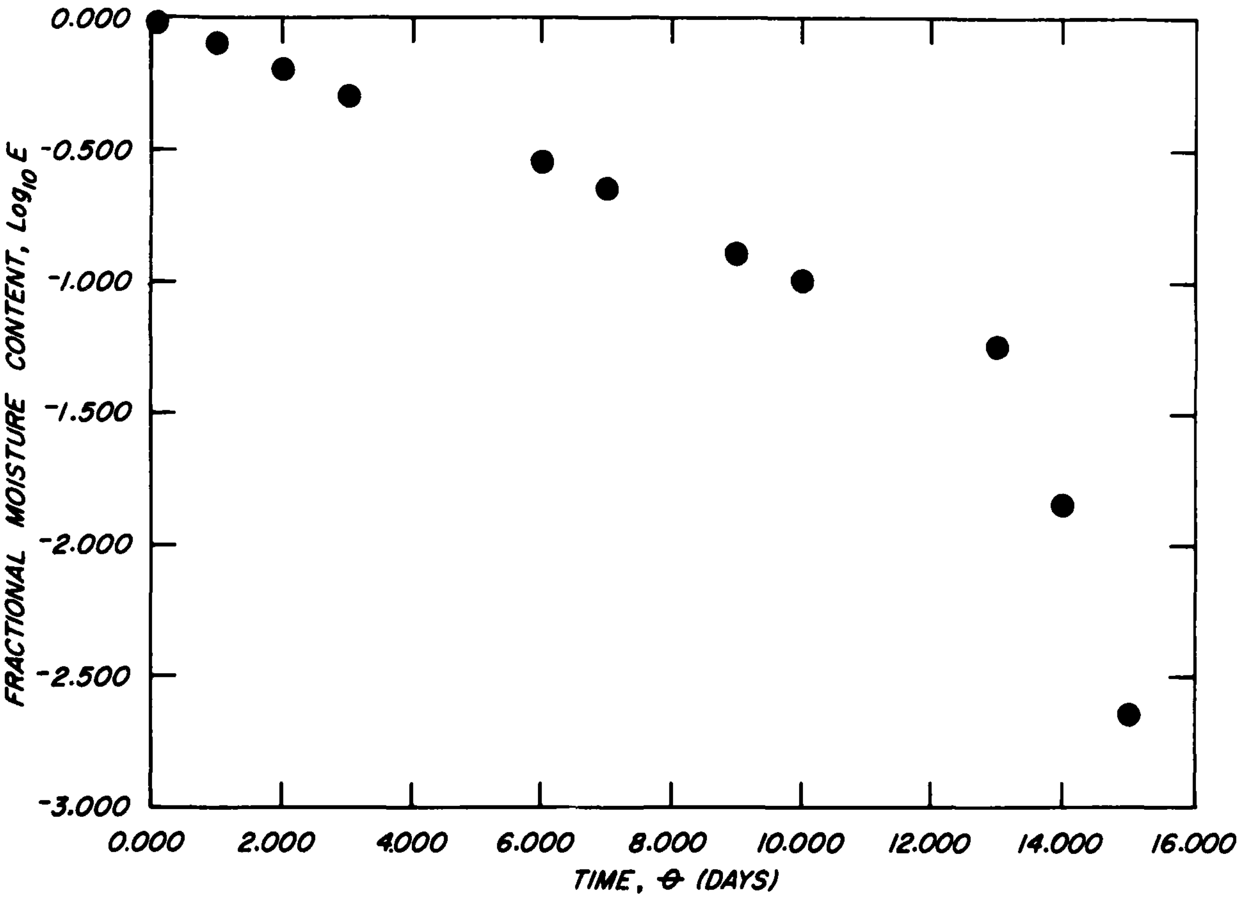


Figure 5.--Typical drying rate curve (tangile) showing approximately linear relationship between log of fractional moisture content and time. (From a computer plotting routine.)
M 144 786

### Interpretation of drying rates

The rate data for the individual boards were transferred to computer cards and correlated with the same function found useful for red oak. The plots of ℓnE versus time were mostly straight lines (figure 5).

Regression analyses of all 83 boards were performed fitting the data to $E = \exp(-b\theta/\ell^{1.52})$. Values of $b_s$ for the various woods are from table 10. Also shown is $f_s$, the ratio of the particular species to red oak ($b = 0.180$ at 120° F). Any wood with a coefficient $f_s$ greater

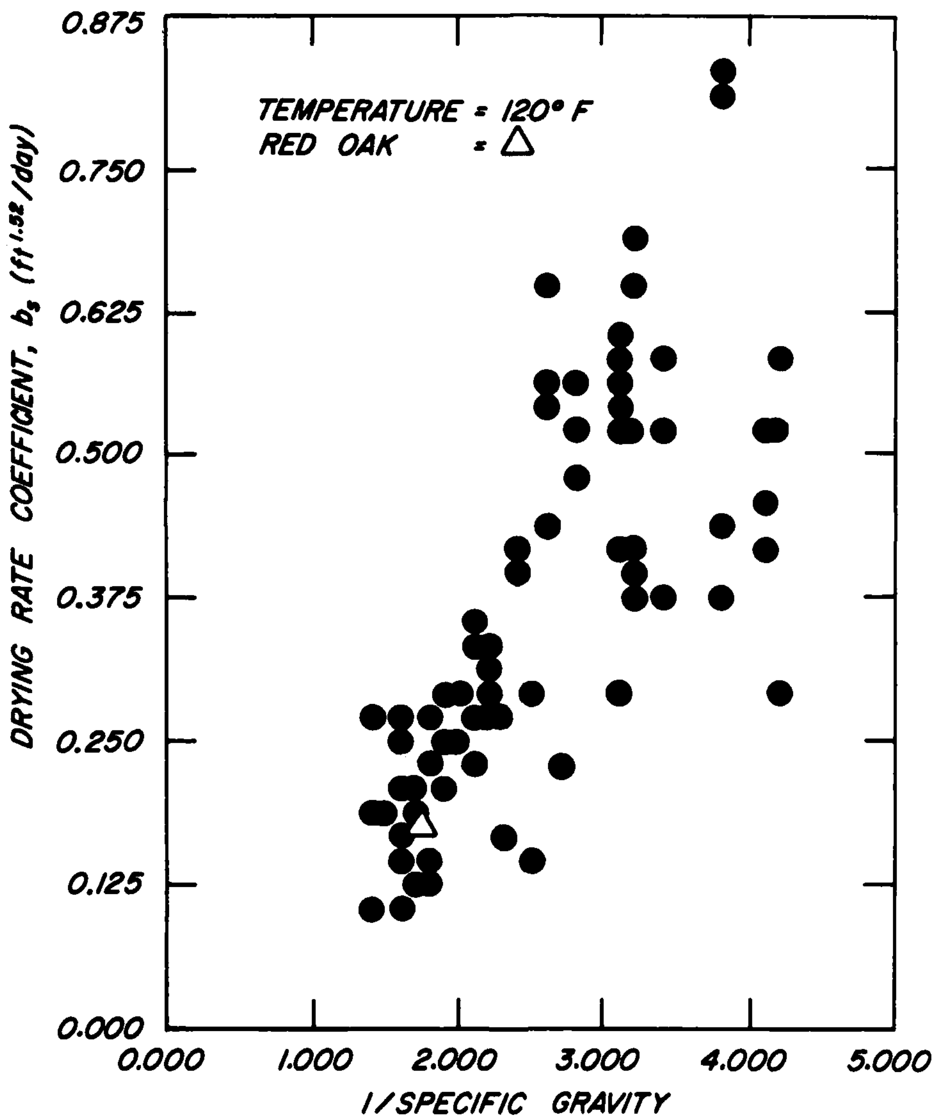


Figure 6.--Correlation of drying rate coefficient $b_s$ to specific gravity at a temperature of 120° F. (From a computer plotting routine.)
M 144 787

than 1 dries faster than red oak; less than 1 dries more slowly than red oak. A simple correlation of empirical drying rate coefficients to specific gravity is $b_s$ plotted against 1/specific gravity (figure 6). This might produce a straight line; however, the scatter in the data is very great, perhaps too great to be useful even as a gross estimate. For the computer modeling, the values of $f_s$ taken from table 10 were the average for multiple observations.

Table 10.--Drying rate coefficient $b_s$ for various Philippine species

| Specimen number | Uncorrected $-B$[1/] | $-b_s$ | $f_s$[2/] | Specific gravity | Common name |
|---|---|---|---|---|---|
| 1 | -.1608 | -.6928 | 3.8488 | .316 | GUBAS |
| 2 | -.1729 | -.6495 | 3.6086 | .316 | GUBAS |
| 3 | -.1112 | -.3815 | 2.1194 | .264 | RARANG |
| 4 | -.1221 | -.4338 | 2.4099 | .264 | RARANG |
| 5 | -.1372 | -.5156 | 2.8646 | .308 | ILANG-ILANG |
| 6 | -.0842 | -.3811 | 2.1172 | .308 | ILANG-ILANG |
| 7 | -.1310 | -.4389 | 2.4385 | .264 | RARANG |
| 8 | -.1447 | -.5141 | 2.8561 | .236 | TANGISANG-BAYAUAK |
| 9 | -.1381 | -.5248 | 2.9154 | .324 | HAMINDANG |
| 10 | -.1498 | -.5568 | 3.0933 | .324 | HAMINDANG |
| 11 | -.1819 | -.5738 | 3.1878 | .296 | KAITANA |
| 12 | -.1108 | -.4256 | 2.3645 | .308 | ILANG-ILANG |
| 13 | -.2486 | -.4553 | 2.5293 | .244 | KAPOK |
| 14 | -.1241 | -.4159 | 2.3108 | .244 | KAPOK |
| 15 | -.1618 | -.4249 | 2.3606 | .244 | KAPOK |
| 16 | -.0794 | -.2821 | 1.5671 | .236 | TANGISANG-BAYAUAK |
| 17 | -.1457 | -.5177 | 2.8761 | .296 | KAITANA |
| 18 | -.0988 | -.3711 | 2.0616 | .296 | KAITANA |
| 19 | -.1598 | -.5547 | 3.0817 | .324 | HAMINDANG |
| 20 | -.1809 | -.5848 | 3.2490 | .324 | HAMINDANG |
| 21 | -.1344 | -.5164 | 2.8686 | .324 | HAMINDANG |
| 22 | -.1647 | -.5389 | 2.9940 | .324 | HAMINDANG |
| 23 | -.1702 | -.5910 | 3.2833 | .324 | HAMINDANG |
| 24 | -.1166 | -.4188 | 2.3269 | .319 | ANABIONG |
| 25 | -.0859 | -.3018 | 1.6768 | .319 | ANABIONG |
| 26 | -.1551 | -.6088 | 3.3824 | .324 | HAMINDANG |
| 27 | -.1224 | -.4199 | 2.3326 | .319 | ANABIONG |
| 28 | -.1492 | -.5729 | 3.1830 | .236 | TANGISANG-BAYAUAK |
| 29 | -.1863 | -.6391 | 3.5507 | .381 | MATANG-ARAU |
| 30 | -.2190 | -.8228 | 4.5714 | .260 | BALILANG-UAK |
| 31 | -.2865 | -.8268 | 4.5936 | .260 | BALILANG-UAK |
| 32 | -.1323 | -.4172 | 2.3180 | .242 | BINUANG |
| 33 | -.1282 | -.4400 | 2.4442 | .381 | MATANG-ARAU |
| 34 | -.1680 | -.5170 | 2.8720 | .242 | BINUANG |
| 35 | -.1502 | -.5214 | 2.8967 | .356 | BALANTI |
| 36 | -.1711 | -.5599 | 3.1108 | .381 | MATANG-ARAU |
| 37 | -.1643 | -.5377 | 2.9875 | .381 | MATANG-ARAU |
| 38 | -.1546 | -.4882 | 2.7122 | .356 | BALANTI |
| 39 | -.1575 | -.5531 | 3.0729 | .356 | BALANTI |

Table 10.--Drying rate coefficient $b_s$ for various Philippine species (cont.)

| Speci-men number | Uncor-rected b[1] | $b_s$ | $f_s$[2] | Specific gravity | Common name |
|---|---|---|---|---|---|
| 40 | -.0936 | -.3250 | 1.8054 | .447 | APANIT |
| 41 | -.0681 | -.2308 | 1.2825 | .366 | MAYAPIS |
| 42 | -.1272 | -.4264 | 2.3691 | .422 | TULO |
| 43 | -.0726 | -.2178 | 1.2099 | .597 | BATITINAN |
| 44 | -.0892 | -.2919 | 1.6217 | .526 | ITANGAN |
| 45 | -.1135 | -.3894 | 2.1631 | .422 | TULO |
| 46 | -.0614 | -.1938 | 1.0768 | .597 | BATITINAN |
| 47 | -.0863 | -.2926 | 1.6255 | .447 | APANIT |
| 48 | -.1156 | -.3601 | 2.0006 | .469 | ANTIPOLO |
| 49 | -.0995 | -.3257 | 1.8092 | .469 | ANTIPOLO |
| 50 | -.1151 | -.3949 | 2.1940 | .422 | TULO |
| 51 | -.0796 | -.2606 | 1.4475 | .478 | BAGTIKAN |
| 52 | -.0872 | -.2549 | 1.4162 | .526 | ITANGAN |
| 53 | -.0664 | -.2096 | 1.1645 | .526 | ITANGAN |
| 54 | -.0522 | -.1467 | .8149 | .549 | PILING-LIITAN |
| 55 | -.1601 | -.3972 | 2.2065 | .316 | DITA |
| 56 | -.1541 | -.4216 | 2.3421 | .316 | DITA |
| 57 | -.1095 | -.2996 | 1.6643 | .394 | MALASANTOL |
| 58 | -.0501 | -.1388 | .7711 | .401 | WHITE LAUAN |
| 59 | -.0960 | -.2663 | 1.4792 | .429 | TANGILE |
| 60 | -.0990 | -.2708 | 1.5047 | .549 | PILING-LIITAN |
| 61 | -.0702 | -.1947 | 1.0816 | .725 | KATONG-MATSIN |
| 62 | -.0799 | -.2216 | 1.2312 | .485 | SAKAT |
| 63 | -.0850 | -.2294 | 1.2742 | .485 | SAKAT |
| 64 | -.0934 | -.2911 | 1.6173 | .510 | RED LAUAN |
| 65 | -.0879 | -.2405 | 1.3364 | .510 | RED LAUAN |
| 66 | -.0516 | -.1336 | .7425 | .576 | PANAU |
| 67 | -.0561 | -.1453 | .8072 | .623 | APITONG |
| 68 | -.0798 | -.2066 | 1.1480 | .592 | KATMON |
| 69 | -.0796 | -.2268 | 1.2603 | .560 | MALABETIS |
| 70 | -.1124 | -.3200 | 1.7780 | .451 | LAGO |
| 71 | -.0813 | -.2076 | 1.1532 | .639 | BOKBOK |
| 72 | -.0940 | -.2677 | 1.4872 | .559 | LOMARAU |
| 73 | -.0737 | -.1907 | 1.0594 | .680 | KATONG-LAKIHAN |
| 74 | -.1090 | -.2782 | 1.5454 | .568 | DANGKALAN |
| 75 | -.0444 | -.1263 | .7019 | .554 | PALOSAPIS |
| 76 | -.0592 | -.1686 | .9367 | .435 | PAHUTAN |
| 77 | -.0867 | -.2470 | 1.3720 | .623 | MIAU |
| 78 | -.0419 | -.1116 | .6200 | .623 | APITONG |
| 79 | -.0767 | -.2788 | 1.5488 | .623 | MIAU |
| 80 | -.0194 | -.1017 | .5651 | .736 | MANARING |
| 81 | -.1181 | -.2637 | 1.4650 | .451 | LAGO |
| 82 | -.0273 | -.1679 | .9326 | .639 | BOK-BOK |
| 83 | -.0907 | -.2616 | 1.4536 | .736 | MARARING |

[1] Values were converted from $\log_{10}$ and corrected to a 1-inch thickness to arrive at $b_s$.

[2] $f_s$ = factor relating relative ease of drying of any species to red oak ($f_s = b_s/b$).

# COMPUTER PROGRAM

<u>Computer Program Description</u>

For the purposes of the analysis, the dryers are assumed to be a rectangular parallelepiped of essentially conventional design: concrete block, wooden built-up roof, overhead fans, fin steam coils or directly gas-fired heaters. The orientation of the structure is axially north-south. Six external heat transfer surfaces were designated: 1. Roof, 2. South wall, 3. East wall, 4. West wall, 5. North wall, and 6. Floor.

Heat loss is assumed to occur in all surfaces (1-6); heat gain by solar radiation is assumed to exist on combinations of up to five surfaces (1-5).

A single overall heat transfer coefficient will be assumed as typical for each of the five surfaces which will combine convective, conductive, and radiative losses. The transmission of solar energy through any surface can be varied from 100 percent (transparent) to 0 percent (opaque).

The original program had the following important assumptions:

1. Time basis was 24 hours (1 day),
2. Solar radiation was uniformly available for each 24-hour period,
3. Venting of exhaust dryer air was continually variable on demand, not "off-on" by steps,
4. Solar energy collection was direct (greenhouse-type) only, and
5. One known drying schedule (rate) was available for red oak.

The deficiencies of this computer program for the current design requirements are obvious:

1. Supplemental solar energy only,
2. Steady state conditions (no diurnal cycle),
3. No indirect collection,
4. Only one drying schedule (drying rate), and
5. No angle to roof as collector.

This program was modified and expanded in order to provide some design information for a kiln using 100 percent solar energy. The following modifications were made:

1. Supplemental solar only was expanded to 100 percent solar with the simplest assumption possible: direct proportions.
2. Because computation of the unsteady state drying rate was found to be approximated by certain averages of cyclic conditions, one average temperature and humidity was used.
3. Indirect collection was added as a dryer design option.
4. Using correlation of experimental drying rate data, a subprogram was added to predict drying rates for any wood or thickness under varying conditions of temperature and relative humidity.
5. Direct and indirect collection through or on a roof structure of varying angle of tilt was added as an option.

Input variables were:

1. Number of board feet,
2. Specific gravity,
3. Initial and final moisture content,
4. Board thickness,
5. Relative drying rate coefficients, $f_s$,
6. A table of b coefficients (red oak),
7. Dryer size and orientation,
8. Number and horsepower of fans,
9. Location, latitude, and elevation of drying site,
10. Monthly average temperatures, relative humidities, and solar radiation,
11. Number and type of collector surface (direct or indirect), and roof angle,
12. Collector solar transmission factor, and
13. Overall heat transfer characteristics of the various dryer (wall or collector) surfaces as selected for each material of construction.

The program has the following daily, monthly, and annual output (c.f. table 11):

<u>Daily Basis</u>

Percent and Millions Btu Heat Demand
- Building losses
- Evaporation
- Sensible heat (wood, building)
- Vent losses (drying air exhaust)
- Heat gain from internal fan motors
- Percent solar and percent supplemental heat

Wood Moisture Content

Absolute Humidity

Vent Rate

EMC

<u>Monthly Basis</u>

Total Heat Loads, Million Btu
- Steam only
- Gas only (direct fire)
- Steam and solar
- Gas and solar

Percent
- Energy demand, vent, building loss, etc.
- Solar energy used
- Fuel saving

Miscellaneous Quantities
- Dryer efficiency, pounds of steam per pound of water evaporated
- Total energy available
- Relative (to roof) effectiveness per unit area of wall orientations
- Heat loss from each wall

Efficiency and orientations of various collecting surfaces
Insolation of each wall
Size of horizontal collector needed, indirect collection, for 100 percent solar

## Annual Summary

Total Solar Radiation (energy demand per 1,000 board feet).

Table 11.--Typical computer output of daily, monthly, and annual information for solar drying in the Philippines

QUEZON CTY. PHIL IS.   ATM PRESS= .993   ALTITUDE= 200.   LATITUDE= 14.7

WOOD TYPE = MAYAPIS   NUMBER FANS = 3   , HORSEPOWER = .50
MH = 6

HEAT REQUIREMENT PERCENT   MILLION BTU   STANDARD

| DAY | BL | EVAP | SHWB | VENT | POW | PC SOL | PC SUP | PC QD | QTOTAL | C TOTAL | CU FT/MIN | TD | E WATER | RH D | HTD | HTH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13.60 | 32.17 | 12.53 | 41.70 | 5.80 | 22.62 | 73.58 | 14.14 | 2.41 | 2.41 | 1237.8 | 110.00 | 752. | 50. | .02840 | .02293 |
| 2 | 17.96 | 35.68 | .00 | 46.36 | 5.04 | 30.13 | 64.83 | 10.68 | 1.82 | 4.23 | 1042.2 | 110.00 | 630. | 50. | .02840 | .02296 |
| 3 | 20.65 | 34.46 | .00 | 44.89 | 5.81 | 34.95 | 59.24 | 9.25 | 1.58 | 5.81 | 877.5 | 110.00 | 527. | 50. | .02840 | .02299 |
| 4 | 23.63 | 33.12 | .00 | 43.25 | 6.67 | 40.34 | 52.99 | 8.06 | 1.37 | 7.18 | 738.9 | 110.00 | 441. | 50. | .02840 | .02302 |
| 5 | 26.89 | 31.66 | .00 | 41.45 | 7.62 | 46.31 | 46.07 | 7.06 | 1.20 | 8.38 | 622.1 | 110.00 | 369. | 50. | .02840 | .02305 |
| 6 | 30.43 | 30.08 | .00 | 39.49 | 8.65 | 52.85 | 38.50 | 6.22 | 1.06 | 9.44 | 523.9 | 110.00 | 309. | 50. | .02840 | .02308 |
| 7 | 34.21 | 28.41 | .00 | 37.39 | 9.75 | 59.94 | 30.31 | 5.52 | .94 | 10.38 | 441.2 | 110.00 | 259. | 50. | .02840 | .02311 |
| 8 | 38.20 | 26.64 | .00 | 35.16 | 10.93 | 67.51 | 21.57 | 4.92 | .84 | 11.22 | 371.5 | 110.00 | 217. | 50. | .02840 | .02314 |
| 9 | 42.35 | 24.81 | .00 | 32.83 | 12.15 | 75.50 | 12.35 | 4.43 | .75 | 11.98 | 312.9 | 110.00 | 182. | 50. | .02840 | .02317 |
| 10 | 46.24 | 23.57 | .00 | 30.19 | 13.31 | 83.15 | 3.54 | 4.04 | .69 | 12.66 | 263.5 | 110.00 | 152. | 50. | .02840 | .02320 |
| 11 | 50.46 | 21.79 | .00 | 27.75 | 14.58 | 91.51 | -6.09 | 3.69 | .63 | 13.29 | 221.9 | 110.00 | 127. | 50. | .02840 | .02323 |
| 12 | 54.67 | 20.00 | .00 | 25.33 | 15.84 | 100.00 | -15.84 | 3.40 | .58 | 13.87 | 186.9 | 110.00 | 107. | 50. | .02840 | .02327 |
| 13 | 58.82 | 18.23 | .00 | 22.95 | 17.10 | 108.50 | -25.60 | 3.15 | .54 | 14.41 | 157.4 | 110.00 | 89. | 50. | .02840 | .02330 |
| 14 | 62.84 | 16.50 | .00 | 20.65 | 18.33 | 116.92 | -35.25 | 2.93 | .50 | 14.91 | 132.6 | 110.00 | 75. | 50. | .02840 | .02333 |
| 15 | 66.81 | 14.82 | .00 | 18.37 | 19.51 | 123.90 | -43.41 | 2.76 | .47 | 15.38 | 110.9 | 110.00 | 63. | 50. | .02840 | .02332 |
| 16 | 70.56 | 13.21 | .00 | 16.23 | 20.62 | 130.43 | -51.05 | 2.61 | .44 | 15.82 | 92.8 | 110.00 | 52. | 50. | .02840 | .02332 |
| 17 | 74.06 | 11.69 | .00 | 14.25 | 21.66 | 136.44 | -58.10 | 2.48 | .42 | 16.25 | 77.6 | 110.00 | 44. | 50. | .02840 | .02331 |
| 18 | 77.28 | 10.29 | .00 | 12.44 | 22.62 | 141.90 | -64.53 | 2.38 | .41 | 16.65 | 64.9 | 110.00 | 37. | 50. | .02840 | .02331 |
| 19 | 80.21 | 8.99 | .00 | 10.80 | 23.50 | 146.80 | -70.30 | 2.29 | .39 | 17.04 | 54.3 | 110.00 | 31. | 50. | .02840 | .02330 |

HEAT REQUIREMENT MTU PER DAY

| DAY | BL | EVAP | SHWH | VENT | POW | SOLAR | SUP | AREA1 | AREA2 | RATIO | PCSH | PER MC | EMCD | EMCA | TM28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .3277 | .7752 | .3020 | 1.0048 | .0917 | .5450 | 1.7731 | 1722.3 | 1685.5 | 7.6 | 22.6 | 60.00 | 8.23 | 13.21 | 80.79 |
| 2 | .3267 | .6490 | .0000 | .8456 | .0917 | .5481 | 1.1794 | 1250.1 | 1221.6 | 5.5 | 30.1 | 51.57 | 8.23 | 13.21 | 80.89 |
| 3 | .3257 | .5434 | .0000 | .7079 | .0917 | .5511 | .9341 | 1065.9 | 1029.6 | 4.7 | 34.9 | 44.52 | 8.23 | 13.21 | 80.98 |
| 4 | .3246 | .4549 | .0000 | .5942 | .0917 | .5542 | .7279 | 905.6 | 869.5 | 4.0 | 40.3 | 38.61 | 8.23 | 13.21 | 81.07 |
| 5 | .3236 | .3809 | .0000 | .4987 | .0917 | .5572 | .5543 | 771.9 | 736.0 | 3.4 | 46.3 | 33.67 | 8.23 | 13.21 | 81.16 |
| 6 | .3225 | .3189 | .0000 | .4186 | .0917 | .5603 | .4081 | 660.3 | 624.7 | 2.9 | 52.9 | 29.53 | 8.23 | 13.21 | 81.26 |
| 7 | .3215 | .2670 | .0000 | .3514 | .0917 | .5633 | .2849 | 567.2 | 531.7 | 2.5 | 59.9 | 26.06 | 8.23 | 13.21 | 81.35 |
| 8 | .3205 | .2235 | .0000 | .2950 | .0917 | .5664 | .1809 | 489.5 | 454.2 | 2.1 | 67.5 | 23.16 | 8.23 | 13.21 | 81.44 |
| 9 | .3194 | .1871 | .0000 | .2476 | .0917 | .5694 | .0931 | 424.5 | 389.5 | 1.9 | 75.5 | 20.73 | 8.23 | 13.21 | 81.54 |
| 10 | .3184 | .1623 | .0000 | .2079 | .0917 | .5725 | .0204 | 374.3 | 339.5 | 1.6 | 83.1 | 18.69 | 8.23 | 13.21 | 81.63 |
| 11 | .3173 | .1370 | .0000 | .1745 | .0917 | .5755 | -.0383 | 329.1 | 294.5 | 1.4 | 91.5 | 16.99 | 8.23 | 13.21 | 81.72 |
| 12 | .3163 | .1157 | .0000 | .1465 | .0917 | .5785 | -.0917 | 291.2 | 256.7 | 1.3 | 100.0 | 15.56 | 8.23 | 13.21 | 81.81 |
| 13 | .3152 | .0977 | .0000 | .1230 | .0917 | .5816 | -.1372 | 259.3 | 225.0 | 1.1 | 108.5 | 14.37 | 8.23 | 13.21 | 81.91 |
| 14 | .3142 | .0825 | .0000 | .1033 | .0917 | .5846 | -.1763 | 232.4 | 198.4 | 1.0 | 116.9 | 13.37 | 8.23 | 13.21 | 82.00 |
| 15 | .3139 | .0696 | .0000 | .0863 | .0917 | .5822 | -.2040 | 211.8 | 177.6 | .9 | 123.9 | 12.53 | 8.23 | 13.24 | 82.02 |
| 16 | .3136 | .0587 | .0000 | .0721 | .0917 | .5797 | -.2269 | 194.4 | 160.1 | .9 | 130.4 | 11.83 | 8.23 | 13.27 | 82.05 |
| 17 | .3134 | .0495 | .0000 | .0603 | .0917 | .5773 | -.2458 | 179.8 | 145.6 | .8 | 136.4 | 11.26 | 8.23 | 13.29 | 82.07 |
| 18 | .3131 | .0417 | .0000 | .0504 | .0917 | .5749 | -.2614 | 167.6 | 133.0 | .7 | 141.9 | 10.75 | 8.23 | 13.32 | 82.10 |
| 19 | .3128 | .0351 | .0000 | .0421 | .0917 | .5725 | -.2742 | 157.3 | 122.5 | .7 | 146.8 | 10.36 | 8.23 | 13.35 | 82.12 |

QUEZON CTY. PHIL IS.   ATM PRESS= .993   ALTITUDE= 200.   LATITUDE= 14.7

WOOD TYPE = MAYAPIS   BOARD THICKNESS= 1.12 IN

COLLECTOR SURFACE =ROOF ANGLE= 0 DEG= ******NONE******   *EAST-WEST*   ******NONE******   DIRECT

| INLET RH | L TEMP F | H TEMP F | SR BTU/DAY/FT2 | HA TEMP F |
|---|---|---|---|---|
| 71.00 | 72.00 | 92.00 | 1911.62 | 82.00 |

| TOTAL HEAT LOAD= | MILLIONS BTU | PERCENT SHW | PERCENT EVAP= | PERCENT BL= | PERCENT VENT= | LB ST/LB W | TH/HHP | PERF |
|---|---|---|---|---|---|---|---|---|
| STEAM ONLY | 13.651 | .00 | 36.26 | 19.57 | 44.18 | 2.94 | 3.41 | |
| GAS ONLY | 14.019 | .00 | 33.17 | 19.86 | 43.00 | 3.01 | 3.50 | |
| STEAM+SOLAR | 17.040 | 63.35 ( 79.07) | 27.29 | 35.57 | 35.38 | 1.36 | 4.26 | 54.2 |
| GAS+SOLAR | 17.498 | 61.09 ( 77.00) | 26.57 | 34.84 | 34.45 | 1.44 | 4.37 | 52.2 |

1 HR 1.00 DAY   ASSUME U= .25 BTU/HR/F/FT2   SOLAR TRANSP EFF= 73.00 PERCENT

DRY WEIGHT WOOD= 6923. LBS   SPEC GRAV= .43   DRYER SIZE L= 12. W= 19. H= 10.   WS= 19. HW= 10. FEET

INITIAL MOIST=60.000 FINAL MOIST=10.303 MONTH = 6 HHF= 8.00 TH/HHF= 4.26 MIL BTU

ND= 19 NUMBERS DAY DRYING   10.8 NET SOLAR RAD MIL BTU

ROOF= 1.000   SOUTH WALL= .323   EAST-WEST WALL= .503   NORTH WALL= .184

UR= .55   US= .12   UEW= .55   UN= .12   UW= .12

U11= .12   U22= .12   U33= .12   U44= .12   12.48 HOURS SUNSHINE

ER= 72.8   ES= 100.0   EEW= 66.1   EN= 100.0   EFOV= 57.2   COLLECTOR EFFICIENCY

5.86   .00   4.93   .00   SOL RAD MIL BTU

## Best Estimates of Collector Area

The main purpose of the computer analysis was to aid in dryer design and provide performance estimates of possible designs. The cost constraint is the limiting design and size factor, and with this in mind two design types were proposed and then examined in detail to determine if they met the performance criteria set up initially. The results of this detailed analysis are in the following section. The actual structural details are presented in the last section of the report.

The two design types selected for consideration were: indirect (external) collector and direct (greenhouse) collector. The production capacity for them was selected to average 1,000 board feet of nominal 1-inch thick lumber per week (4,000 board feet per 28 days). Because the only source of energy to be considered is solar, the actual drying time would vary from the most favorable months of March through June to the least of December through February in the Philippines. Wood species and board thickness are also factors causing variation. The kiln size selected to hold 4,000 board feet per charge was 19 x 12 x 10 feet high. The four species of typical commercial Philippine woods dried at FPL--mayapis, red lauan, white lauan, and tangile--were compared at two levels of initial moisture content, 60 percent and 30 percent.

A simplifying assumption used to derive these estimates of collector area is the choice of a daily average condition in the collector (external or greenhouse) of 110° F, 50 percent relative humidity, for the drying purposes. (This corresponds to a drying EMC of 8.2 percent.) Admittedly, this assumption is crude, but it was the only expeditious choice to make at this time.

### External collector kiln

The advantages of external collection are twofold: Orientation of the collector can be optimized independent of kiln structure; and maximum size of the collector is not dependent upon size and shape of kiln. Because the latitude of the Island of Luzon in the Philippines is about 14° north, a horizontal surface (0°) was judged, for reasons of lower cost of design, a good compromise on maximum solar interception for 12 months of the year. (Usual guide for yearly collection, angle of collector should equal the latitude.)

The collector cover material considered in this analysis has the properties of a polyester-fiberglass-reinforced plastic (commercial trade name, Kalwal). The single-layer Kalwal has an overall heat transfer coefficient of $U = 1$, and a double layer has a $U = 0.55$. The coefficients for insulated walls and the ground were 0.12. The effectiveness of single and double (standard 1/2-inch) "glaze", compared at two moisture levels for four species, was represented as the estimate of collector area needed to dry to 10 percent MC 4,000 board feet of 1.125-inch green lumber every 28 days, 12 months per year (table 12). Also estimated was average board footage dried, in 28 days, per square

Table 12.--External horizontal collector areas required to dry 4,000 board feet in 28 days

| Species | Collector area required | | Dryer capacity:collector area ratio | |
|---|---|---|---|---|
| | Single cover | Double cover | Single cover | Double cover |
| | $Ft^2$ | $Ft^2$ | $Bd.ft./ft^2$ | $Bd.ft./ft^2$ |
| Dried From 60 Percent to 10 Percent Moisture Content | | | | |
| Mayapis | 973 | 745 | 4.11 | 5.37 |
| Red lauan | 1,246 | 952 | 3.21 | 4.20 |
| White lauan | 1,121 | 869 | 3.57 | 4.60 |
| Tangile | 1,082 | 826 | 3.70 | 4.84 |
| Average | 1,106 | 848 | 3.65 | 4.75 |
| Dried From 30 Percent to 10 Percent Moisture Content | | | | |
| Mayapis | 497 | 377 | 8.05 | 10.6 |
| Red lauan | 591 | 450 | 6.77 | 8.89 |
| White lauan | 625 | 480 | 6.40 | 8.33 |
| Tangile | 523 | 398 | 7.64 | 10.1 |
| Average | 559 | 426 | 7.22 | 9.48 |

foot of exposed horizontal cover surface. Table 13 shows the variation of collector area needed to dry 4,000 board feet per 28 days for each month for one species, mayapis, with a green moisture content of 60 percent.

To reduce heat losses, a double cover is preferable to a single cover (table 12), thereby decreasing the area of the collector. An average collector area of 848 square feet represents 3.7 times the roof area. The difference between these four wood species is not great. The advantage of air drying to 30 percent before solar drying is apparent in that for any given area of collector, the capacity of the solar dryer would be doubled. For a fixed area (745 square feet), the rate would be higher for March, April, May, June, and October, and lower for January, February, July, August, September, November, and December (table 13). The actual external collector area suggested for one solar kiln design in the Philippines is discussed in "Proposed Solar Kiln Design."

### Direct (greenhouse) kiln

Direct collection of solar energy implies capture of radiant energy through the transparent structural walls of a building itself. In the case of wood drying, one or all five walls are transparent to solar radiation, which is collected internally by some darkened baffle structure. Past efforts in dryer design have been almost exclusively

Table 13.--Monthly variation of external horizontal double-layer collector area needed to dry 4,000 board feet of mayapis in 28 days from 60 percent to 10 percent moisture content

| Month | Cover area | Month | Cover area | Month | Cover area |
|---|---|---|---|---|---|
| | $Ft^2$ | | $Ft^2$ | | $Ft^2$ |
| January | 1,040 | May | 471 | September | 780 |
| February | 1,071 | June | 567 | October | 723 |
| March | 592 | July | 854 | November | 764 |
| April | 435 | August | 813 | December | 823 |
| | | AVERAGE | 745 | | |

of this type. The advantage is low-cost transparent walls for a controlled drying environment, as well as energy interception, particularly if cheap replacement films can be used. The disadvantages are that no cheap, stable films are available; the effective collector area per board foot drops as the volume and capacity of the building increase; and, as the cost of the transparent wall increases, the economics of each wall of different collecting efficiency becomes a cost factor consideration.

Single and double collector covers of the same fiberglass-reinforced polyester resin plastic sheeting (Kalwal) had the same overall heat transfer coefficients as in the external-type kiln.

The expected performances of combinations of the five walls or surfaces, designated roof (R), east-west (E-W), south (S), and north (N), were compared (table 14) at one moisture level with the orientation of the major axis north-south. The superiority of the double-layer glaze is apparent. Even though the computer model underestimates the diffuse radiation component, which is quite high in tropical high-humidity areas, the numbers do show an advantage to adding the east-west wall. The south wall adds cost without a great deal of increased capacity. The addition of a north wall, even at a tropical latitude has a negative value. Further analysis of roof only and roof plus east-west (table 15) for two moisture levels shows that the combination of a transparent roof and east-west walls is the optimum.

The effect of the orientation of the major axis north-south or east-west (table 16) is not great, but capacity does increase by 10 to 20 percent; thus, if practical for a dryer of this size and scope, north-south axis is preferred. It should be noted that change in orientation changes the collector area.

In summary, direct collection appears to be inferior to the external collector; if direct collection is used, the north-south orientation of

Table 14.--Comparison of four combinations of collector surface at one dryer orientation (long axis north-south) from 30 percent to 10 percent moisture content[1]

| Species | Dryer capability | | Dryer capacity:collector area ratio | |
|---|---|---|---|---|
| | Single cover[2] | Double cover[1] | Single cover[2] | Double cover[1] |
| | Bd.ft./28 days | Bd.ft./28 days | Bd.ft./$ft^2$ | Bd.ft./$ft^2$ |
| | | ROOF (228 $ft^2$) | | |
| Mayapis | 1,528 | 1,980 | 6.70 | 8.68 |
| Red lauan | 1,200 | 1,556 | 5.26 | 6.82 |
| White lauan | 1,268 | 1,644 | 5.56 | 7.21 |
| Tangile | 1,388 | 1,796 | 6.09 | 7.88 |
| Average | 1,346 | 1,744 | 5.90 | 7.65 |
| | | ROOF, EAST-WEST (608 $ft^2$) | | |
| Mayapis | 1,520 | 3,732 | 2.50 | 6.14 |
| Red lauan | 1,196 | 2,940 | 1.97 | 4.84 |
| White lauan | 1,264 | 3,104 | 2.08 | 5.11 |
| Tangile | 1,384 | 3,384 | 2.28 | 5.57 |
| Average | 1,366 | 3,290 | 2.20 | 5.42 |
| | | ROOF, EAST-WEST, SOUTH (728 $ft^2$) | | |
| Mayapis | 1,344 | 4,148 | 1.85 | 5.70 |
| Red lauan | 1,056 | 3,264 | 1.45 | 4.48 |
| White lauan | 1,120 | 3,448 | 1.54 | 4.74 |
| Tangile | 1,270 | 3,772 | 1.74 | 5.18 |
| Average | 1,198 | 3,658 | 1.65 | 5.03 |
| | | ROOF, EAST-WEST, SOUTH, NORTH (848 $ft^2$) | | |
| Mayapis | 424 | 3,956 | 0.50 | 4.67 |
| Red lauan | 336 | 3,112 | 0.40 | 3.67 |
| White lauan | 356 | 3,284 | 0.42 | 3.87 |
| Tangile | 388 | 3,600 | 0.46 | 4.25 |
| Average | 376 | 3,488 | 0.45 | 4.12 |

[1] 12 x 19 x 10 feet.

[2] Single-cover Kalwal, U = 1.0, transmission = 90 percent; double-cover Kalwal, U = 0.55, transmission = 73 percent.

Table 15.--Greenhouse-type solar kiln capacity estimates

| Species | Roof and East-West (608 $ft^2$) | | | | Roof only (228 $ft^2$) | | | |
|---|---|---|---|---|---|---|---|---|
| | Dryer capability | | Dryer capacity:collector area ratio | | Dryer capability | | Dryer capacity:collector area ratio | |
| | Single cover | Double cover | Single cover | Double cover | Single cover | Double cover | Single cover | Double cover |
| | Bd.ft./28 days | Bd.ft./28 days | Bd.ft./$ft^2$ | Bd.ft./$ft^2$ | Bd.ft./28 days | Bd.ft./28 days | Bd.ft./$ft^2$ | Bd.ft./$ft^2$ |
| DRIED FROM 60 PERCENT TO 10 PERCENT MOISTURE CONTENT | | | | | | | | |
| Mayapis | 708 | 1,740 | 1.16 | 2.86 | 712 | 924 | 3.12 | 4.05 |
| Red lauan | 532 | 1,308 | 0.88 | 2.15 | 536 | 696 | 2.35 | 3.05 |
| White lauan | 628 | 1,540 | 1.03 | 2.53 | 628 | 816 | 2.75 | 3.58 |
| Tangile | 624 | 1,532 | 1.03 | 2.52 | 624 | 812 | 2.73 | 3.56 |
| Average | 623 | 1,530 | 1.03 | 2.52 | 625 | 812 | 2.74 | 3.56 |
| DRIED FROM 30 PERCENT TO 10 PERCENT MOISTURE CONTENT | | | | | | | | |
| Mayapis | 1,520 | 3,732 | 2.50 | 6.14 | 1,528 | 1,980 | 6.70 | 8.68 |
| Red lauan | 1,196 | 2,940 | 1.97 | 4.84 | 1,200 | 1,556 | 5.26 | 6.82 |
| White lauan | 1,264 | 3,104 | 2.08 | 5.11 | 1,268 | 1,644 | 5.56 | 7.21 |
| Tangile | 1,384 | 3,384 | 2.28 | 5.57 | 1,388 | 1,796 | 6.09 | 7.88 |
| Average | 1,341 | 3,290 | 2.21 | 5.42 | 1,346 | 1,744 | 5.90 | 7.65 |

Table 16.--Comparison of drying capacity (12 x 19 x 10 feet) of two major axis orientations from 30 percent to 10 percent moisture content

| Species | Orientations: East-West | | Orientations: North-South | |
|---|---|---|---|---|
| | Dryer capability | Dryer capacity: collector area ratio | Dryer capability | Dryer capacity: collector area ratio |
| | Bd.ft./28 days | Bd.ft./$ft^2$ | Bd.ft./28 days | Bd.ft./$ft^2$ |
| ROOF, EAST-WEST | | | | |
| | ($468\ ft^2$) | | ($608\ ft^2$) | |
| Mayapis | 3,084 | 6.51 | 3,732 | 6.14 |
| Red lauan | 2,428 | 5.19 | 2,940 | 4.84 |
| White lauan | 2,564 | 5.48 | 3,140 | 5.11 |
| Tangile | 2,808 | 6.00 | 3,384 | 5.57 |
| Average | 2,721 | 5.80 | 3,290 | 5.42 |
| ROOF, EAST-WEST, SOUTH | | | | |
| | ($658\ ft^2$) | | ($728\ ft^2$) | |
| Mayapis | 3,732 | 5.67 | 4,148 | 5.70 |
| Red lauan | 2,948 | 4.48 | 3,264 | 4.48 |
| White lauan | 3,104 | 4.72 | 3,448 | 4.73 |
| Tangile | 3,392 | 5.16 | 3,772 | 5.18 |
| Average | 3,290 | 5.01 | 3,658 | 5.03 |

major axis is recommended; the roof and east-west walls collect sufficient radiation; and a double layer of cover is desirable, even in the tropics. It should be cautioned that these conclusions are specific to the dryer size and dimensions, properties of one cover material, and climate of one locale in the Philippines, i.e., the immediate vicinity of Manila.

# PROPOSED SOLAR KILN DESIGNS

Two solar kilns are proposed to meet the requirements and limitations found in this analysis.

In one design, the collector is external to the kiln so that the collector area and oriention will be free of the constraint of the geometry of the kiln and can thus be large, and so that the drying chamber can be heavily insulated to reduce heat losses. This should provide high drying capacity and the necessary production rate for drying lumber from the green condition. The other design is the lower cost greenhouse type in which the collector is an integral part of the kiln. It will not have the drying capacity to meet the necessary production rates when kiln drying lumber from the green (60 percent) condition, but it will have for partially air dried (30 percent) lumber. This is a feasible alternative; air drying from 60 to 30 percent is not unreasonably long (table 2).

While the proposed kilns are designed with the necessary cost and production rate requirements in mind for use in an actual commercial operation, there will be enough unknowns in some of the construction and performance details that the kilns should be considered test kilns to be evaluated under commercial conditions before they can be considered final designs.

## External Collector Design

In the external-type kiln, the drying chamber is a well insulated compartment, and the solar collector is external to it and oriented horizontally (schematic, figure 7). A 1,000-board-foot prototype is under construction at the Forest Products Laboratory, Madison, Wisconsin (figure 8).

The proposed design (figure 7) has a capacity of 4,000 board feet of nominal 1-inch-thick lumber. The external collector has approximately 850 square feet of effective collector area--enough to meet the required production rate of 4,000 board feet in 28 days, drying from 60 to 10 percent moisture content (table 10). The collector is 12 feet wide by approximately 78 feet long (long dimension oriented north-south). The drying chamber (north end of collector) is designed to hold an 8-foot-wide load of lumber 16 feet long. The internal dimensions of the drying chamber are approximately 12 by 19 by 10 feet high.

The drying chamber is wood-frame construction with heavy insulation, on a foundation of a single row of concrete blocks on a concrete footing. The floor is gravel. From the inside out, the wall construction is: 1/2-inch-thick exterior grade plywood, sheet polyethylene vapor barrier, 2 x 4 studs on 16-inch centers, stud space filled with roll insulation, 1-inch-thick polystyrene sheet insulation, and 1/2-inch-thick exterior grade plywood. Roof construction is similar with rafters, rafter space filled with loose insulation, black roll roofing, and a slight pitch

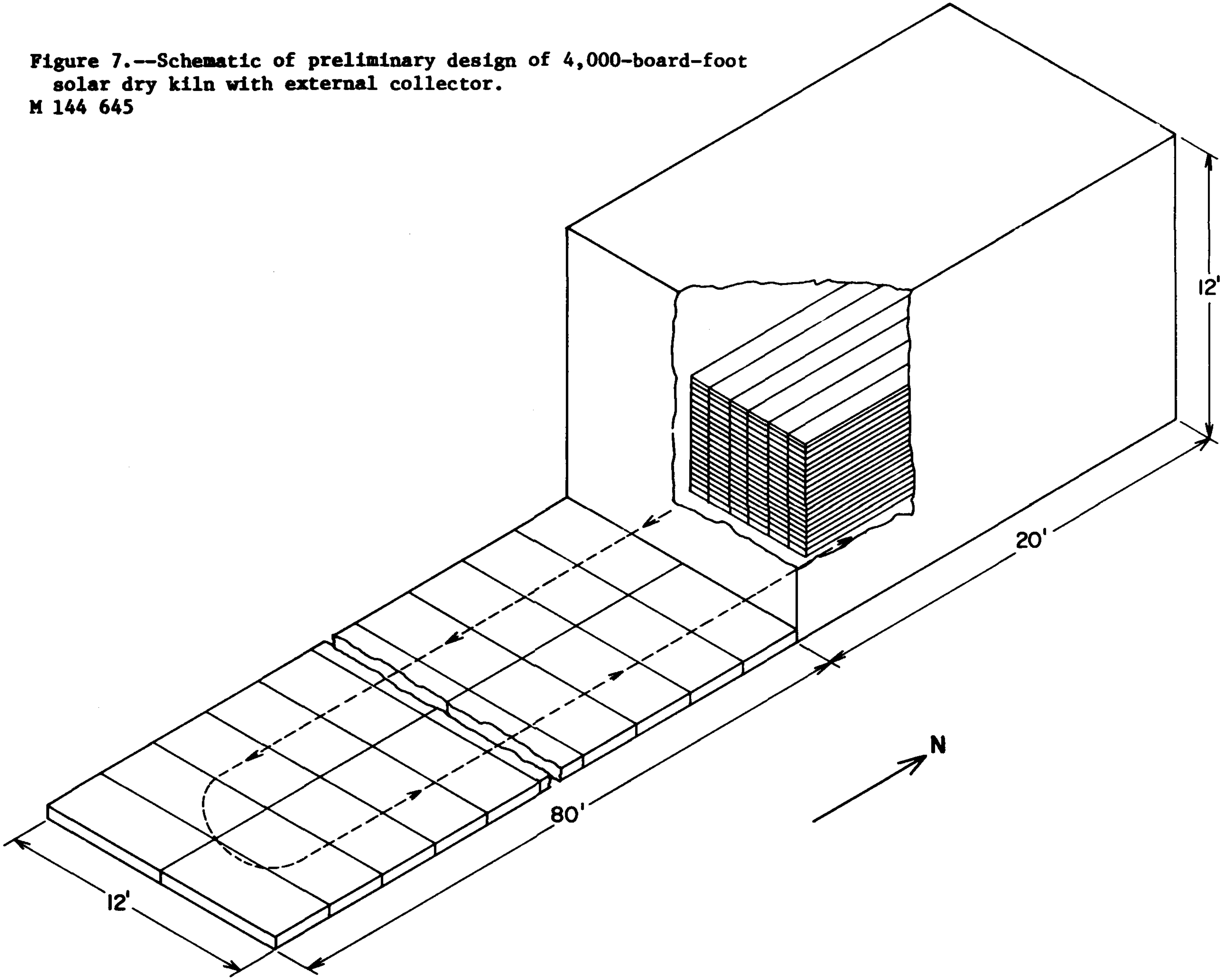


Figure 7.--Schematic of preliminary design of 4,000-board-foot solar dry kiln with external collector.
M 144 645

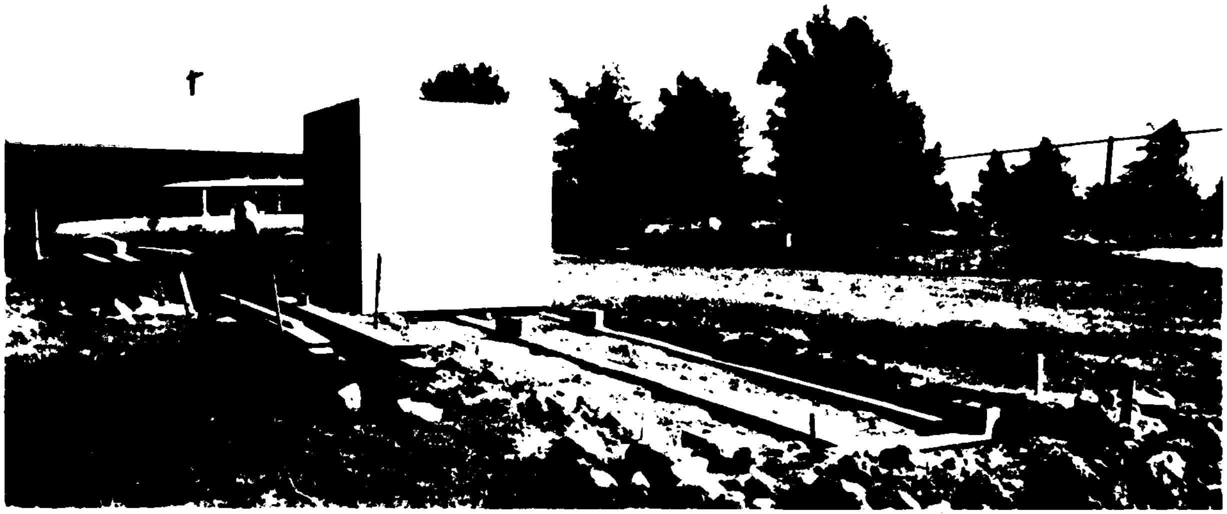

Figure 8.--Partially completed 1,000-board-foot prototype solar kiln built at Forest Products Laboratory, Madison, Wisconsin, U.S.
M 144 769-4

to the east or west. A 10- by 7-foot double swing wood frame door, tightly fitting and well gasketed, is located on the north wall of the drying chamber.

The controls include a humidifier, vents, fans, and a blower to circulate air through the collector. A centrifugal-type humidifier is recommended to eliminate nozzle clogging problems or the need for expensive pneumatic systems. The type HJ centrifugal humidifier manufactured by the Bahnson Company, Winston-Salem, North Carolina, suitable for this purpose, is capable of evaporating 8 gallons of water per hour. The unit comes equipped with a humidistat that controls up to 95 percent relative humidity and can operate at temperatures up to 150° F. The humidifier uses a 1/4-horsepower electric motor with the option of 115-volt, 60-hertz, single phase, or 110-volt, 50-hertz, single phase. The unit operates from a water line and requires a reasonably constant pressure between 10 and 35 psi.

Vents are to be operated by a humidistat and damper motor so that they will open and close automatically with changes in relative humidity in the kiln. A Honeywell model H404A 1003 humidistat (20 to 80 percent relative humidity) and a Honeywell model M436A1041A damper motor are suitable for the purpose. Three overhead fans, approximately 24 inches in diameter and each powered by 1/2-horsepower motors, will provide circulation through the load. A blower capable of delivering at least 1,500 cubic feet per minute can induce flow through the collector.

The foundation for the collector is concrete blocks, one high, on a sand footing. A treated-wood sill plate is anchored to the blocks all

the way around the perimeter. The blocks and sill also extend down the center of the length of the collector to within 3 feet of the end. This separates the in- and out-flow of air to and from the kiln, and provides for a circuit of air from the leaving air side of the load, through one length of the collector, around to the other side of the collector and back down the length of the collector again, into the kiln and through the load of lumber. The length of the collector is oriented north-south with the kiln on the north end. The collector has a 9-inch slope to the south for drainage.

The collector glazing is a fiberglass-reinforced polyester material especially formulated for solar energy collection. The material recommended is manufactured by Kalwall Corp., Manchester, N.H., and the trade name is Sun-lite. A premium grade is available (0.04 inch thick) that has increased resistance to ultraviolet and heat degradation. The service life of this material is estimated by the manufacturer as 20 years. Sun-lite can be purchased as prefabricated, double-glazed collector panels, and it is recommended that these prefabricated panels be used in the collector. The panels are made with an aluminum framework (aluminum battens are provided for bridging between adjacent panels and angles for the perimeter of the collector), and thermal expansion problems within a panel are minimized because aluminum and Sun-lite have nearly equal thermal expansion. The panels do have a thermal expansion of 5/32 inch per 10 feet per 100° F, so adequate spacing between panels is necessary. Manufacturer's literature is available for installation instructions. Each panel is 33-3/4 inches by 75-5/8 inches. Solar energy transmission is 77 percent at 0° angle of incidence, and 73 percent at a 30° angle of incidence (38° maximum angle of incidence on December 21 at 15° N latitude). The overall heat transfer coefficient is 0.55 Btu per hour per square foot per degree F.

Soil, dark crushed rock, or other material will serve as the solar energy absorbing surface. Charcoal, if readily available, would work very well. The space between this surface and the bottom of the collector panels should be 6 inches. A sheet plastic vapor barrier on the earth or between the earth and the rock or charcoal will minimize condensation in the collector.

The earth collector will offer some energy storage capacity for night-time drying. No attempt was made to estimate the effectiveness of the storage. When the kiln is actually built the evaluation program should include plans to investigate this effectiveness.

The construction costs, including labor, are based largely on material and labor costs in the Philippines. Where this information was lacking, United States prices were used. Local material and equipment can be used for most of the kiln but the recommendations are to import the collector panels, humidifier, humidistat, and damper motor from the U.S. unless nearly identical products can be obtained locally, or perhaps from Japan. The estimated total cost of the kiln is US$5,650 (table 17). The drying chamber, kiln controls, and collector are estimated at US$1,105, $1,690, and $2,855, respectively.

Table 17.--Estimated cost of solar dry kiln with external collector

| Component | Cost (1975) |
|---|---|
| | U.S. dollars |
| Drying chamber | |
| Foundation | $ 60 |
| South wall | 130 |
| North wall (including door) | 165 |
| East wall | 210 |
| West wall | 210 |
| Roof | 310 |
| Floor (gravel) | 20 |
| Total drying chamber cost | $1,105 |
| Kiln controls | |
| Humidifier (Bahnson model HJ)[1] | $ 665 |
| Damper motor (Honeywell model M436A1041A)[1] | 85 |
| Humidistat for vents (Honeywell model H404A)[1] | 90 |
| Three fans (24-inch diameter) | 200 |
| Three electric motors (1/2 hp, 115 volt) | 350 |
| Blower | 200 |
| Installation labor and miscellaneous costs | 100 |
| Total control cost | $1,690 |
| Collector | |
| Foundation | $ 75 |
| 54 Sun-lite glazing panels (1/2 x 33-3/4 x 75-5/8 in.)[1] | 2,315 |
| 50 aluminum battens (8 feet long)[1] | 200 |
| 21 aluminum edge angles (8 feet long)[1] | 185 |
| Sealant | 80 |
| Total collector cost | $2,855 |
| TOTAL KILN COST | $5,650 |

[1] Including packing and surface shipping to Manila.

## Direct (Greenhouse) Design

The greenhouse kiln design is wood-frame construction (2 x 4's; 16-7/8-inch centers to accommodate the collector panel size) with collectors on the roof, east, and west walls. The capacity of the kiln is 4,000 board feet of nominal 1-inch lumber. The internal dimensions of the kiln are 20 by 12 by 12 feet high. The long dimension of the kiln is oriented north-south.

The recommended collectors are the prefabricated resin plastic panels (1/2 by 33-3/4 by 75-5/8 inches) as recommended for the external collector kiln. They are placed on the outside of the wall stud and roof rafter framework, with the necessary battens and edge angle. Corrugated sheet metal is placed on the inside of the framework as the absorbing surface. The corrugated sheet metal (and stud and rafter faces) should be painted with a selective coating that maximizes energy absorption and minimizes radiation losses. The 3-M Company, Minneapolis, Minnesota, manufactures a suitable coating with the trade name Nextel Black Velvet Coating No. 101-C10.

The north and south walls of the kiln are the same heavily insulated wood-frame construction as in the external collector kiln. The door could be located in either the north or south wall. The kiln controls will be the same as in the external collector kiln except that the blower is not necessary in the greenhouse kiln.

The estimated cost of constructing the greenhouse-type solar kiln is US$4,605 (table 18).

Table 18.--Estimated cost of greenhouse-type solar kiln

| Component | Cost (1975) |
|---|---|
| | U.S. dollars |
| Drying chamber and collector | |
| Foundation | $ 60 |
| South wall | 160 |
| North wall (including door) | 195 |
| Collector for roof, east, and west walls | |
| 42 collector panels (1/2 x 33-3/4 x 75-5/8 in.)[1] | 1,805 |
| 50 aluminum battens (8 feet long) | 200 |
| 15 aluminum edge angles (8 feet long) | 135 |
| Sealant | 60 |
| Wood framework | 175 |
| Corrugated metal absorber | 250 |
| Selective coating (3 gallons @ $35.00) | 100 |
| Total drying chamber & collector cost | $3,140 |
| Kiln controls | |
| Humidifier (Bahnson model HJ)[1] | $ 665 |
| Damper motor (Honeywell model M436A1041A)[1] | 85 |
| Humidistat for vents (Honeywell model H404A)[1] | 90 |
| Three fans (24-inch diameter) | 200 |
| Three electric motors (1/2 hp, 115 volt) | 350 |
| Installation labor and miscellaneous costs | 75 |
| Total control cost | $1,465 |
| TOTAL KILN COST | $4,605 |

[1] Including packaging and surface shipping to Manila.

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